American Journal of Student Research

Review Article

Valvular Heart Diseases: Advances in Biology, Treatments and Future Technologies

Jiayin Li

Santa Margarita Catholic High School, 22062 Antonio Pkwy, Rancho Santa Margarita, CA 92688, USA

ABSTRACT

Heart valves maintain unidirectional blood flow, ensuring effective cardiac function. Valvular heart disease (VHD) is a major global cause of morbidity. Given the scale and impact of valvular heart disease, this review focuses on the structures and mechanisms of the four major valves, aortic, mitral, tricuspid, and pulmonary valves comprehending the biology and clinical aspects of both congenital and acquired valvular diseases. This manuscript reviews emerging updates in transcatheter mitral valve repair, transcatheter aortic valve replacement, and stem cells-based approaches for the management of various valvular diseases. Additionally, the article provides insights into computational models and artificial intelligence in next generation valvular therapies.

Keywords: Heart; Cardiology; Diseases; Treatments; Technology

INTRODUCTION

"Valvular heart disease (VHD) is a significant cause of morbidity worldwide, with an estimated 74 million people affected in 2019" (1). To understand its effects on health, it is essential to examine the structure and function of the heart and its valves. The human heart consists of four chambers, left and right ventricles and left and right atriums (Figure 1). The heart valves ensure unidirectional flow of blood by facilitating the movement of deoxygenated blood into the lungs and circulating oxygenated blood throughout the body (2). Impairment in the functions of heart valves significantly affects the pumping efficiency and heart function. Common valve diseases include valvular stenosis, valvular regurgitation, ventricular dysfunction, arterial dilation, and atresia (3). Clinically, valve diseases arise congenital or acquired.

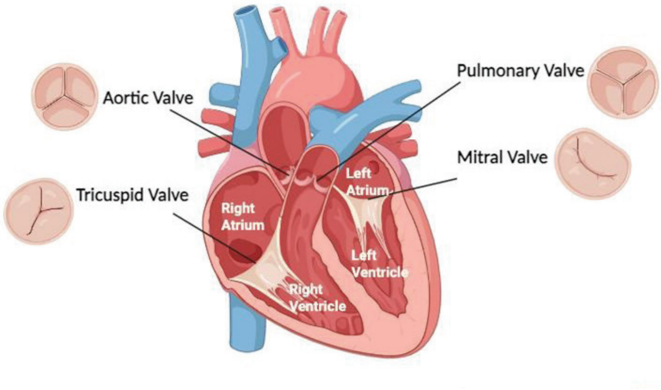

Figure 1. Anatomy of heart and valves.

Corresponding author: Jiayin Li, E-mail: amy081116@gmail.com.

Received May 2, 2025**; Accepted** June 12, 2025
https://doi.org/10.70251/HYJR2348.33132138

Congenital valve disease includes abnormal valve shape, size, structure, and formation of leaflets (3), whereas acquired heart diseases include rheumatic fever, infective endocarditis, and aging (4). Regurgitation refers to the backward flow of blood resulting from inadequate closure of the valve. Stenosis is characterized by the thickening of the valve leaflets. Atresia describes the absence of a valve. Among these valve dysfunctions, mitral regurgitation (MR) is an especially important case, involving mitral arrhythmias or heart failure. This dysfunction may require surgical intervention, such as valve repair or replacement. During mitral valve regurgitation, the valve leaflets do not close properly, causing the backward flow of blood. Individuals with this condition often experience an irregular and rapid heartbeat, higher blood pressure, and congestive heart failure. Although it appears to be mild and progresses slowly, it can still pose serious health risks (5).

Heart valves ensure one-way blood flow by opening and closing in response to pressure changes. They allow blood, carrying oxygen and nutrients, to be delivered to the cells while also removing waste products. For the heart to function efficiently, its valves need to function properly; otherwise, the heart is forced to exert more energy to pump blood, or diseases may develop. One of the major challenges of valvular diseases is heart failure, as the heart must pump harder to compensate for poorly functioning valves (6).

VALVES BIOLOGY

The heart contains four main types of valves: the tricuspid valve, pulmonary valve, mitral valve, and aortic valve (Table 1) (Figure 1). Each valve plays a crucial role in regulating blood flow through different chambers and vessels of the heart. The tricuspid valve regulates blood flow between the right atrium and the right ventricle, while the pulmonary valve regulates blood flow from the right ventricle to the pulmonary artery. The mitral valve manages blood flow between the left atrium and left ventricle, and the aortic valve controls blood flow from the left ventricle into the aorta.

Generally, the valve function depends on the contraction and relaxation of the heart muscle, causing the opening and closing of the valves, which allows unidirectional flow (7). The four valves are being separated into two categories: Atrioventricular valves (tricuspid and mitral) and semilunar valves (Aortic and Pulmonary).

The tricuspid consists of three cusps or leaflets: the anterior, posterior, and septal leaflets. The base of each

Table 1. Detailed Anatomy and Physiological Function of the Four Major Heart Valves

Heart Valve	Anatomy	Function
Tricuspid Valve	Composed of three leaflets: anterior, posterior, and septal. The leaflets are attached to the fibrous annulus and connected via chordae tendineae to papillary muscles in the right ventricle. These structures stabilize the valve during ventricular contraction and prevent prolapse into the right atrium.	Ensures unidirectional blood flow from the right atrium to the right ventricle. It closes during ventricular contraction to prevent backflow of blood into the atrium.
Pulmonary Valve	Made up of three semilunar cusps: anterior, left, and right. Located at the junction between the right ventricle and the pulmonary artery. It lacks chordae tendineae and opens based on pressure differences.	Controls blood flow from the right ventricle into the pulmonary artery and onward to the lungs for oxygenation. Closes during ventricular relaxation to prevent blood from flowing back into the ventricle.
Mitral Valve	Has two leaflets (anterior and posterior), making it a bicuspid valve. Supported by chordae tendineae and papillary muscles in the left ventricle.	Regulates blood flow from the left atrium to the left ventricle, opening during diastole and closing during systole to prevent backflow. Proper function is essential for efficient systemic circulation.
Aortic Valve	Consists of three semilunar cusps: right, left, and posterior. Located at the exit of the left ventricle, leading into the ascending aorta. It does not require chordae tendineae, and its cusps are stabilized by pressure and anatomical structures like aortic sinuses.	Allows oxygen-rich blood to flow from the left ventricle into the aorta during ventricular contraction. Closes during relaxation to prevent retrograde flow from the aorta into the heart.

cusp is anchored to a fibrous ring called the annulus that provides stability. Thin, string-like structures, called chordae tendineae, connect the edges of the valve leaflets to the papillary muscles in the right ventricle, preventing the valve leaflets from being pushed backward into the right atrium that causes backward blood flow. The papillary muscles pull on the chordae tendineae, ensuring the integrity of valve leaflets the mitral valve has the similar structure as the tricuspid valve, but has two leaflets: anterior and posterior. The aortic valve has three cusps: right, left, and posterior and annulus located at the base of the valve to stabilize it. Unlike the atrioventricular valves, the aortic valve does not require chordae tendineae for support. Instead, the cusps are stabilized by the pressure of the blood flowing through the valve. There are small pockets behind each cusp known as aortic sinuses that help to maintain the valve's shape and function. The pulmonary valve has the similar structure characteristics as the aortic valve (8).

VALVULAR PATHOLOGY

A valvular disease can develop whenever there is a dysfunction in the structure or function of the heart valves (Table 2) (9). Tracking to embryology, the heart has the role of pumping blood, which creates the circular pattern of blood flow. When the heart valves fail to form properly during this period, congenital valve diseases can arise. These defects mainly emerge from an abnormal valve development during the embryonic period, within the first six weeks of pregnancy, when the heart is developing from a simple tube-like structure into a more structured heart (10). In the United States, congenital valve disease affects approximately 1 in every 100 children with around 500,000 adults in the United States currently having congenital heart disease there are about 500,000 adults who have congenital heart disease (11). Among infants who are diagnosed with congenital heart defects, research shows that around 5–6% of the cases are associated with chromosomal abnormalities, while 3–5% are linked to single-gene disorders. Additionally, about 2% are connected to environmental factors during pregnancy, such as infections or certain maternal health conditions (12). As the condition progresses, seizure disorders, phenylketonuria, or insulin-dependent diabetes may develop. Additionally, heart valve defects include stenosis, heart muscle abnormalities, a hole located on the wall of the heart, heart failure, and atherosclerosis aggravates the pathology.

A major challenge with congenital valve disease is that it often remains undetected until later in life, because symptoms such as chest pain, fatigue, dizziness, shortness of breath, or heart murmurs (13) that are not always presented in childhood, so early diagnosis is difficult. These symptoms typically emerge until the disease has significantly worsened, typically until middle age. Moreover, there are many variations of congenital valve disease, including aortic valve stenosis, coarctation of the aorta, Ebstein's anomaly, patent ductus arteriosus, pulmonary valve stenosis, and more (14). These variability highlights the importance of earlier detection and more personalized treatments.

In contrast, acquired valve diseases develop after birth, often due to aging or preexisting diseases that can lead to the hardening of tissue and restriction in blood flow. As people age, their heart valves are more likely to become stiff and leak, which is known as aortic valve stenosis and mitral regurgitation (15). For example, aortic stenosis results in a compromised blood flow that impairs cardiac function resulting in ventricular hypertrophy (16).

Table 2. Overview of Congenital and Acquired Valve Diseases: Causes, Symptoms, and Treatments

Type of Valve Disease	Causes	Symptoms	Treatments
Congenital Valve Disease	Genetic mutations, abnormal valve formation during early fetal development, environmental risk factors during pregnancy.	Fatigue and poor weight gain, cyanosis (bluish skin or lips due to low oxygen levels), heart murmur detected in infancy or childhood.	Medications, surgery (valve repair or replacement), minimally invasive procedures, life monitoring devices.
Acquired Valve Diseases	Aging, rheumatic fever or infections, calcification of valve leaflets abnormal structural heart conditions.	Progressive shortness of breath, chest pain or pressure, fatigue, dizziness, or fainting , swelling in the legs.	Medications, TAVR or TMVR for high-risk patients, open-heart surgery.

Treatment of valve disease starts with changing to a healthy lifestyle or medications. Eventually, in severe cases, the heart valve request repaired or replaced. Medications diuretics and vasodilators help with controlling blood pressure thereby relieving valvular workload. Surgical approach has been prescribed for fixing valve leaflets including positioning, reshaping, reattaching or separating the leaflets.

CHALLENGES

Early diagnosis of valvular diseases are challenging because they remain asymptomatic; however, early interventions improve the chances of recovery (17). Diagnostic tests, such as echocardiogram, chest X-ray, stress test, and screening tests are necessary for detection. Unfortunately, many patients often attribute their symptoms to easier causes such as lack of rest or high levels of stress (18). As a result, patients experience serious complications including heart failure, stroke, thrombogenesis, arrhythmias, infection, pulmonary hypertension, and death in severe cases (19).

Additionally, the risk factors include age, poor hygiene and nutrition, and hurdle valve treatment. In the United States, approximately 13.2% of individuals aged 75 years or above experiencing modern to severe valvular heart disease (20). In many developing countries, access to treatments is limited due to underdeveloped healthcare systems or financial struggles. Therefore, improvements in healthcare practices are warranted (21). Surgical challenges include heart valve infections, excessive bleeding, transient ischaemic attack and kidney dysfunction. Even though the risk of mortality is about 2%, surgical interventions are likely to induce undesirable outcome (22).

EMERGING TREATMENTS

As technology advances, innovative treatments and interventions are emerging. Transcatheter Aortic Valve Replacement (TAVR) (Figure 2) is a procedure to replace a narrowed or diseased aortic valve to treat aortic stenosis (23). TAVR offers an alternative to traditional surgery, allowing for faster recovery. During this minimally invasive procedure, employing catheter, artificial or xenogeneic valves are used to replace the damaged aortic valve (24). Similarly, Transcatheter Mitral Valve Repair (TMVR) (Figure 2) is another minimally invasive procedure used to repair a damaged mitral valve. During TMVR, a catheter clips to fasten the leaflets to prevent backflow of blood and leakage. The clip closes the valve partly, allowing the blood flow (25).

Currently, mesenchymal stem cells (MSCs) (Figure 2) are emerging to regenerate damaged valve tissue. MSCs from bone marrow and fat tissue have the potential to differentiate into valvular interstitial cells (VICs) or valvular endothelial cells (VECs). VICs are abundant in fibrosa, spongiosa, and the ventricularis layers of the valve (26). These cells are organized into five phenotypes and functions to maintain the physiological valve structure and function, allows to activate cellular repair processes (proliferation, migration, and matrix modeling), and calcification in the heart valve (27). VECs play a crucial role in valvular leaflet integrity including protection against calcification, inflammation and fibrosis (28). MSCs derived VICs and VECs are promising to repair or replace the damaged valve tissue through minimally invasive injection thereby avoiding complicated surgical procedures (29) .

CURRENT-STATE-OF ART

Currently practiced heart valve replacements have clinical limitations. Mechanical valves require lifelong use of blood thinners, while bioprosthetic valves wear out within 10 to 20 years. Interestingly, a bioengineered valve could address these issues by lasting longer and growing with the patient. Creating a bioengineered valve involves advanced techniques such as nanotechnology, 3D printing, and tissue engineering (30). Researchers aim to develop bioengineered heart valves that closely mimic the function of natural heart valves. One approach is self-

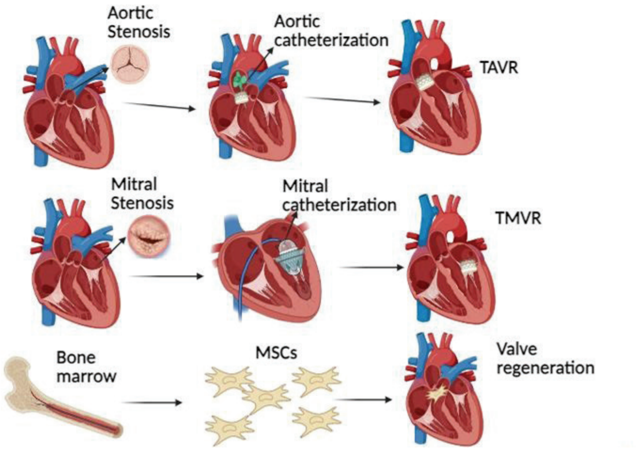

Figure 2. Approaches in valvular disease managements.

seeding valves, which offer a faster and more practical alternative to traditional bioengineered valves. Instead of growing patient cells in a lab prior to implantation, which is a slow and complex process, self-seeding valves are coated with antibodies that attract the host cells post-implantation (31).

X-linked cardiac valvular dysplasia is a genetic condition that affects the heart valves, causing them to thicken and malfunction. One or more heart valves become thickened and fail to function, leading to blood leaking through the affected valves, most commonly the mitral or aortic valve. Valve regurgitation induces cardiac overload, potentially causing symptoms such as chest pain and shortness of breath. Additionally, the mitral or aortic valve prolapse, further preventing proper closure and causing valve regurgitation (32).

Of the more than 300,000 heart valve replacements performed worldwide each year, 40% to 60% are xenograft bioprosthetics (33). A xenogenic heart valve is a valve transplanted from an animal to a human, typically from pig or cow tissue (34). Pig hearts closely resemble human hearts, allowing for direct transplantation, whereas cow heart tissue requires further modifications. Animal models, particularly pigs and sheep, are commonly used in heart valve research because their heart anatomy and valve structure closely resemble those of humans. Smaller animals such as chickens, mice, and zebrafish are used to study congenital valve disease, as their embryos can be easily manipulated to examine how specific genes or environmental factors influence valve formation. Larger animals, including sheep and pigs, are used to test new valve replacement and repair devices due to their heart size, structure, and biological responses. For example, mouse embryo models are effective to study different genes on cardiac and valve development, as well as lineage tracing of cells. Zebrafish and chicken embryos, which have transparent heart tissues, allow for high-resolution imaging of the heart and vasculature, as well as monitoring of blood flow dynamics. Chicken embryos are particularly useful for surgical interventions that alter hemodynamics in heart development (35).

An important study demonstrated for the first time that lab-created heart valves implanted in young lambs showed reduced calcification and improved hemodynamics after one year follow-up. This approach has the potential to provide a growing heart valve for children with congenital heart disease, reducing the need for multiple heart surgeries. Currently, growing heart valves are limited, demanding multiple surgeries and cost (36).

Computational models of heart valves use numerical simulations to study the mechanics, fluid dynamics, and interactions between valve structures and blood flow. Bioprosthetic heart valves (BHVs) are commonly used to replace damaged heart valves, their durability remains a challenge. Computational models help researchers understand the mechanisms behind BHV deterioration and optimize new valve designs. Key components of these models include accurate representations of valve structures, realistic biomaterial properties that change over time, and appropriate physiological conditions (37).

FUTURE PERSPECTIVE

Artificial intelligence (AI), a revolutionary advancement in cardiovascular disease treatment, has been increasingly used in the diagnosis and treatment of valvular heart disease. AI has the ability to detect clinical signs that might be missed or misinterpreted by a physician. Evidently, “AI was shown to be over twice as sensitive at detecting audible valvular heart disease (corresponding to moderate or greater disease) than physicians (94.1% vs. 41.2%), with similar specificity (84.5% vs. 95.5%)” (38). Additionally, AI assists in ECG interpretation, particularly in identifying specific patterns associated with valvular heart disease that are yet to be achieved. Contrastingly, out of 33,371 patients, AI detected moderate to severe aortic stenosis in 1,224 cases. However, the positive predictive value was only 10%, while the negative predictive value was 99%, suggesting that AI produces a high rate of false positives. Hence, further improvements in AI algorithms are warranted. Ultimately, the use of robots in performing surgical procedures represents the most advanced application of AI in valvular heart disease treatment. Currently, these robotic systems have only been tested in animal experiments, however the field is rapidly developing.

CONCLUSION

In conclusion, congenital and acquired valvular heart diseases elicit serious threats to global cardiovascular health. Developments in diagnostic methods, surgical procedures, and stem cell therapies offer support to millions of sufferers. Early diagnosis remains a major problem and further research and advancements in artificial intelligence are required to improve treatments, especially in surgery and diagnostic accuracy. Additionally, further research into bioengineered valves and minimally invasive procedures are warranted to design personalized solutions.

DECLARATION OF CONFLICT OF INTERESTS

The author(s) declare that there are no conflicts of interest regarding the publication of this article.

REFERENCES

1. Daghem MG, Hornik B & Abu-Fadel MA. Valvular heart disease–related mortality between middle- and high-income countries: a global analysis from 2000 to 2019. *Global Heart*. Available from: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC11733992/ (accessed on 2025-1-5)
2. Overview: Heart valve diseases. Available from: https://www.ncbi.nlm.nih.gov/books/NBK536872/ (accessed on 2025-1-5)
3. Stephens EH, Kearney DL & Grande-Allen KJ. Insight into pathologic abnormalities in congenital semilunar valve disease based on advances in understanding normal valve microstructure and extracellular matrix. *Cardiovascular Pathology.* 2012; 21 (1): 46–58. Available from: https://doi.org/10.1016/j.carpath.2011.01.002 (accessed on 2025-1-5)
4. Valvular heart disease. Available from: https://www.heartandstroke.ca/en/heart-disease/conditions/valvular-heart-disease/ (accessed on 2025-1-5)
5. Mitral valve regurgitation—Symptoms and causes. Available from: https://www.mayoclinic.org/diseases-conditions/mitral-valve-regurgitation/symptoms-causes/syc-20350178 (accessed on 2025-1-8)
6. Heart Valves: What They Are and How They Work. Available from: https://my.clevelandclinic.org/health/body/17067-heart-valves (accessed on 2025-1-13)
7. Heart Valves, Anatomy and Function. Available from: https://www.columbiadoctors.org/treatments-conditions/heart-valves-anatomy-and-function (accessed on 2025-1-17)
8. The Heart Valves—Tricuspid—Aortic—Mitral—Pulmonary—TeachMeAnatomy. Available from: https://teachmeanatomy.info/thorax/organs/heart/heart-valves/ (accessed on 2025-1-21)
9. Heart Valve Disorders | Conditions & Treatments | UTSW. Available from: http://utswmed.org/conditions-treatments/heart-valve-disorders/ (accessed on 2025-1-22)
10. Sun R, Liu M, Lu L, Zheng Y & Zhang P. Congenital Heart Disease: Causes, Diagnosis, Symptoms, and Treatments. *Cell Biochemistry and Biophysics.* 2015; 72 (3): 857–860. Available from: https://doi.org/10.1007/s12013-015-0551-6 (accessed on 2025-1-22)
11. Factors Contributing to Congenital Heart Disease. Available from: https://www.cincinnatichildrens.org/health/c/factors-chd (accessed on 2025-1-27)
12. O'Donnell A & Yutzey KE. Mechanisms of heart valve development and disease. Development (Cambridge, England), 147(13), dev183020. Available from: https://doi.org/10.1242/dev.183020 (accessed on 2025-2-3)
13. Congenital Valve Disease | Aurora Health Care. Available from: https://www.aurorahealthcare.org/services/heart-vascular/conditions/congenital-valve-disease (accessed on 2025-2-10)
14. Congenital heart disease—Types. Available from: https://www.nhs.uk/conditions/congenital-heart-disease/types/ (accessed on 2025-2-19)
15. Acquired Heart Valve Disease Symptoms: Tiredness, Chest Pain, Swelling in Legs - HealthXchange. Available from: https://www.healthxchange.sg:443/heart-lungs/heart-disease/acquired-heart-valve-disease-symptoms-tiredness-chest-pain-swelling-legs (accessed on 2025-2-22)
16. Bartoli-Leonard F & Aikawa E. Heart Valve Disease: Challenges and New Opportunities. *Frontiers in Cardiovascular Medicine.* 2020; 7: 602271. Available from: https://doi.org/10.3389/fcvm.2020.602271 (accessed on 2025-2-25)
17. Heart Valve Diseases—Diagnosis | NHLBI, NIH. Available from: https://www.nhlbi.nih.gov/health/heart-valve-diseases/diagnosis (accessed on 2025-2-26)
18. Heart Valve Diseases - What Are Heart Valve Diseases? | NHLBI, NIH. Available from: https://www.nhlbi.nih.gov/health/heart-valve-diseases (accessed on 2025-3-3)
19. Aikawa E, Blaser MC, Singh SA, Levine RA & Yacoub MH. Challenges and Opportunities in Valvular Heart Disease: From Molecular Mechanisms to the Community. *Arteriosclerosis, Thrombosis, and Vascular Biology*. 2024; 44 (4): 763–767. Available from: https://doi.org/10.1161/ATVBAHA.123.319563 (accessed on 2025-3-5)
20. Howell EJ & Butcher JT. Valvular heart diseases in the developing world: Developmental biology takes center stage. *The Journal of Heart Valve Disease.* 2012; 21 (2): 234–240. Available from: (accessed on 2025-3-8)
21. Aortic valve replacement—Risks. Available from: https://www.nhs.uk/conditions/aortic-valve-replacement/risks/ (accessed on 2025-3-20)
22. Transcatheter Aortic Valve Replacement (TAVR). Transcatheter Aortic Valve Replacement (TAVR) | NHLBI, NIH. Available from: https://www.nhlbi.nih.gov/health/tavr (accessed on 2025-3-24)
23. Spears J, Al-Saiegh Y, Goldberg D, Manthey S & Goldberg S. TAVR: A Review of Current Practices and Considerations in Low-Risk Patients. *Journal of Interventional Cardiology.* 2020, 1–13. Available from: https://doi.org/10.1155/2020/2582938 (accessed on 2025-3-27)
24. Transcatheter Mitral Valve Repair (TMVr). Transcatheter Mitral Valve Repair (TMVr) | University of Michigan Health. Available from: https://www.uofmhealth.org/conditions-treatments/transcatheter-mitral-valve-repair-tmvr (accessed on 2025-4-2)

25. Liu AC, Joag VR & Gotlieb AI. The Emerging Role of Valve Interstitial Cell Phenotypes in Regulating Heart Valve Pathobiology. *The American Journal of Pathology.* 2007; 171 (5): 1407–1418. Available from: https://doi.org/10.2353/ajpath.2007.070251 (accessed on 2025-4-7)
26. Guo Y, Yu Y, Hu S, Chen Y & Shen Z. The therapeutic potential of mesenchymal stem cells for cardiovascular diseases. *Cell Death & Disease.* 2020; 11 (5): 1–10. Available from: https://doi.org/10.1038/s41419-020-2542-9 (accessed on 2025-4-10)
27. Butcher JT & Nerem RM. Valvular endothelial cells and the mechanoregulation of valvular pathology. *Philosophical Transactions of the Royal Society B: Biological Sciences.* 2007; 362 (1484): 1445–1457. Available from: https://doi.org/10.1098/rstb.2007.2127 (accessed on 2025-4-15)
28. *In vivo* autologous recellularization of a tissue-engineered heart valve. Are bone marrow mesenchymal stem cells the best candidates? - ScienceDirect. Available from: https://www.sciencedirect.com/science/article/pii/S0022522307007696 (accessed on 2025-4-17)
29. Bioengineering living heart valves. Asia Research News. Available from: https://www.asiaresearchnews.com/content/bioengineering-living-heart-valves (accessed on 2025-4-21)
30. Jordan JE, Williams JK, Lee S-J, Raghavan D, Atala A & Yoo JJ. Bioengineered self-seeding heart valves. *The Journal of Thoracic and Cardiovascular Surgery.* 2012; 143 (1): 201–208. Available from: https://doi.org/10.1016/j.jtcvs.2011.10.005 (accessed on 2025-4-25)
31. X-linked cardiac valvular dysplasia. MedlinePlus Genetics. Available from: https://medlineplus.gov/genetics/condition/x-linked-cardiac-valvular-dysplasia/ (accessed on 2025-4-28)
32. About the Xenograft Bioprosthetic Heart Valve. Healthline. Available from: https://www.healthline.com/health/heart-health/xenograft-bioprosthetic-heart-valve (accessed on 2025-5-4)
33. Bloomfield P. Choice of heart valve prosthesis. *Heart.* 2002; 87 (6): 583–589. Available from: https://heart.bmj.com/content/87/6/583 (accessed on 2025-5-8), https://doi.org/10.1136/heart.87.6.583
34. Kheradvar A, Zareian R, Kawauchi S, Goodwin RL & Rugonyi S. Animal Models for Heart Valve Research and Development. *Drug Discovery Today: Disease Models.* 2018; 24: 55–62. Available from: https://doi.org/10.1016/j. ddmod.2018.04.001 (accessed on 2025-5-8)
35. Lab-created heart valves can grow with the recipient. University of Minnesota. Available from: https://twin-cities.umn.edu/news-events/lab-created-heart-valves-can-grow-recipient (accessed on 2025-5-10)
36. Zakerzadeh R, Hsu M-C & Sacks MS. Computational Methods for the Aortic Heart Valve and its Replacements. *Expert Review of Medical Devices*. 2017; 14 (11): 849–866. Available from: https://doi.org/10.1080/17434440.2017.1389 274 (accessed on 2025-5-12)
37. Zakerzadeh, R., Hsu, M.-C., & Sacks, M. S. Computational methods for the aortic heart valve and its replacements. Expert Review of Medical Devices, 14(11), 849–866. Available from: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6542368/ (accessed on 2025-05-15).
38. Bhaya J, Aggarwal NR, Berenstein A, Arora RR & Desai M. Artificial intelligence in heart valve disease: diagnosis, innovation, and treatment—a state-of-the-art review. Frontiers in Cardiovascular Medicine. Available from: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC11795922/ (accessed on 2025-5-17)