Current applications and future perspectives of artificial intelligence in valvular heart disease

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INTRODUCTION

Valvular heart disease (VHD) represents one of the foremost contributors to mortality and morbidity globally. With the aging population growing, the incidence of VHD in older adults has risen significantly by 45% over the past 30 years.[1] The complexity and heterogeneity of VHD highlight the importance of early diagnosis and individualized therapeutic approaches. Although diagnostic and therapeutic advancements have been made limitations still exist, such as inadequate sensitivity of conventional diagnostic methods and the lack of personalized treatment plans. Diagnosis and treatment of VHD heavily depend on complex imaging data and dynamic pathological changes. Artificial intelligence (AI), with its advanced image processing and machine learning capabilities, is proving valuable in detecting subtle valve lesions and creating three-dimensional models for complex cases. AI integrates real-time data for dynamic treatment strategies and risk assessments, improving diagnostic efficiency in resource-limited settings. Therefore, integration of AI technology holds promise for enhancing VHD management.

APPLICATION OF AI IN DIAGNOSIS OF VHD

Enhanced accuracy of image analysis

AI has significantly improved the accuracy of VHD diagnosis through deep learning algorithms, such as convolutional neural networks (CNNs). These algorithms extract image features and identify complex patterns that traditional methods may miss. Saitta *et al.* demonstrated that deep learning can efficiently assess the aortic root, improving preoperative planning.[2] Moreover, AI processes large volumes of imaging data from echocardiography, computed tomography (CT), and magnetic resonance imaging (MRI) scans, reducing human error and enhancing diagnostic consistency. As AI systems continuously learn from new data, their diagnostic accuracy increases, supporting clinicians in identifying valvular disorders and improving outcomes. These factors highlight the increasing importance of AI in diagnosing VHD and offer strong support for bettering diagnostic and therapeutic outcomes (Figure 1).

Development of intelligent screening tools

AI-driven tools, such as machine learning models analyzing electrocardiogram signals and heart sounds, offer enhanced diagnostic accuracy compared to traditional methods. For example, machine learning-based electrocardiogram models have shown good predictive ability for left-sided valvular conditions like aortic stenosis and mitral regurgitation.[3] Meanwhile, the vision transformer (ViT)-based AI model extract features from raw phonocardiogram signals, achieved 99.9% diagnostic accuracy in detecting VHD, significantly outperforming manual detection methods.[4] These technologies reduce analysis time from 25 min to under one second, marking a major improvement in diagnostic precision and efficiency. Although most studies currently rely on retrospective datasets, prospective studies

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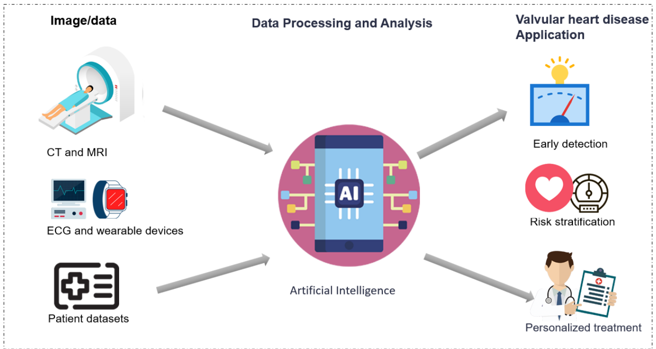

Figure 1: The application of AI in VHD. AI: artificial intelligence; VHD: valvular heart disease; CT: computed tomography; MRI: magnetic resonance imaging; ECG: electrocardiogram.

will validate these models for clinical application.

Risk stratification and treatment planning

In the management of VHD, risk assessment is essential for formulating individualized therapeutic approaches. Machine learning algorithms are increasingly enhancing models, such as EuroSCORE II and transcatheter aortic valve replacement (TAVR), enabling more accurate surgical risk assessments. The PREDICT-TAVR model demonstrated excellent predictive performance in assessing bleeding risk after TAVR, outpacing traditional risk models. By integrating an online calculator and visual aids, the PREDICT-TAVR model enables clinicians to assess bleeding risk and tailor management strategies, improving the safety and quality of care for patients with VHD. AI can analyze patient datasets to identify factors correlated with adverse outcomes, helping clinicians optimize treatment strategies. It also assists surgeons in selecting appropriate surgical approaches and predicting postoperative complications.[5]

INTEGRATING AI WITH DIGITAL TWINS IN VHD

AI plays a crucial role in digital twin technology, which uses real-time and historical data to create virtual models of patients. These digital twins assist in personalized treatment planning and have practical applications in managing VHD.[6] For example, Dowling *et al.* used digital twins to simulate valve implantation outcomes, optimizing surgical strategies and predicting complications.[7] The integration of wearable devices further enhances digital twins, enabling real-time monitoring of physiological changes. In complex VHD cases such as severe aortic stenosis, digital twins provided insights into predicting perivalvular leakage and optimizing valve fit, enhancing decision-making for physicians.[8]

During the postoperative recovery phase, digital twins continue to provide valuable support. By updating with physiological data, they allow clinicians to monitor recovery progress and adjust treatment protocols as needed. This technology also assists in long-term follow-up care, providing insights into prognosis.

INTEGRATING AI WITH 3D PRINTING FOR VHD

The integration of AI and 3D printing technology has opened new avenues for managing VHD. Using data from CT or MRI scans, 3D-printed models replicate the patient's anatomical structure, allowing for virtual experimentation before the procedure. Furthermore, the combination of 3D printing and digital twins offers novel pathways for personalized treatment strategies in VHD. Following the construction of a personalized digital model, clinicians can conduct virtual experiments, ensuring that the final 3D-printed model aligns with clinical requirements. Consequently, 3D printing produce implants tailored to patient needs.[9] Custom designs not only enhance valve functionality, but also mitigate complications while allowing for material selection according to specific criteria. Moreover, AI guides real-time adjustments in implant design, ensuring biocompatibility and clinical needs. This integration propels advancements in precision medicine, enhancing healthcare quality, and providing safer, more effective therapeutic options.

FUTURE DIRECTIONS AND INNOVATIONS IN AI FOR VHD

Looking ahead, the future of AI, digital twin technology, and 3D printing in VHD management will focus on advancing personalized medicine, improving risk stratification, predicting adverse events, and developing novel biomaterials. AI leverages real-time physiological, genomic, and imaging data to optimize digital twin models, which accurately characterize individual conditions, diagnostic and therapeutic guidance. AI-driven risk stratification models predict postoperative complications such as valve dysfunction, infection, or reintervention, supporting targeted treatment strategies.

In materials science, 3D printing innovations aim to enhance the mechanical performance and biocompatibility of printed valves. The synergy between AI, digital twin technology, and 3D printing streamlines manufacturing processes and improves prosthetic valves durability and long-term functionality.

To accelerate clinical translation, collaborations between academia and industry are essential. For example, a study (registration number: ChiCTR2400086685) is investigating AI in interventional treatments for structural heart diseases, including VHD, to assess AI-based risk stratification tools. These trials validate emerging technologies and generate data to support clinical adoption.

By integrating predictive analytics, risk stratification, precision intervention, AI, digital twin technology, and 3D printing transform VHD diagnosis and treatment, offer safer, efficient, and personalized options while driving medical innovation.

CHALLENGES AND LIMITATIONS

Despite the transformative potential of AI, digital twin, and 3D printing in VHD management, several challenges remain. These include concerns about data privacy, algorithmic bias, lack of standardized regulations, and high technical costs. Addressing these issues will require solutions, such as federated learning and data encryption to protect patient privacy, as well as diverse training datasets to reduce bias. International regulatory frameworks and financial support for the development of these technologies will help overcome barriers to widespread adoption. Furthermore, training healthcare professionals is crucial to ensure effective integration of these technologies into clinical practice. These strategies will facilitate the safe, efficient, and equitable application of these technologies in healthcare and ultimately improving patient outcomes.

CONCLUSION

The integration of AI, digital twin technology, and 3D printing presents transformative opportunities for the management of VHD, from early diagnosis to individualized therapeutic strategies. These technologies are anticipated to significantly enhance patient outcomes and alleviate the burden on healthcare systems. Through interdisciplinary collaboration and innovation, the future of VHD management will increasingly rely on the synergy of digital health, AI, and advanced manufacturing technologies.

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Author Contributions

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Ethical Approval

Not applicable.

Informed Consent

Not applicable.

Conflict of Interest

Author have no conflicts of interest to declare.

Use of Large Language Models, AI and Machine Learning Tools

None declared.

Data Availability Statement

No additional data.

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