The application of artificial intelligence in tissue repair and regenerative medicine related to pediatric and congenital heart surgery: a narrative review

Jeevan Francis[1], Joseph George[2], Edward Peng[3], Antonio F. Corno[4,*]
1 Department of Cardiothoracic Surgery, Aberdeen Royal Infirmary, Aberdeen. UK
2 Division of Cardiovascular Surgery, The Hospital for Sick Children, Toronto, Canada
3 Royal Hospital for Children, Glasgow and University of Glasgow, Glasgow, UK
4 Faculty of Science and Engineering, Manchester Metropolitan University, Manchester, UK, and School of Engineering, University of Leicester, Leicester, UK

*Correspondence to: Antonio F. Corno, MD, FRCS (Glasgow), FETCS, FACC, FHEA, tonycorno2@gmail.com.
orcid: 0000-0003-4374-0992 (Antonio F. Corno)

Abstract

Artificial intelligence and machine learning have the potential to revolutionize tissue repair and regenerative medicine in the field of pediatric and congenital heart surgery. Artificial intelligence is increasingly being recognized as a transformative force in healthcare with its ability to analyse large and complex datasets, predict surgical outcomes, and improve surgical education and training with the use of virtual reality and surgical simulators. This review explores the current applications of artificial intelligence in predicting surgical outcomes, improving peri-operative decision-making, and facilitating training for surgeons, particularly in low-income countries. By leveraging advanced algorithms and simulations, artificial intelligence can analyse intricate patient data and anatomical variations, enabling early detection of congenital heart defects and optimising surgical approaches. Ultimately, while barriers such as inconsistent data quality and limited resources remain, the advancement of artificial intelligence technologies offers a promising avenue to enhance regenerative medicine related to patient care and surgical education in pediatric and congenital heart surgery.

Key words: artificial intelligence; congenital database; congenital heart surgery; learning machine; low-income countries; pediatric heart surgery; regenerative medicine; surgical decision-making; surgical outcomes; surgical training

doi: 10.4103/REGENMED.REGENMED-D-24-00013
How to cite this article: Francis J, George J, Peng E, Corno AF. The application of artificial intelligence in tissue repair and regenerative medicine related to pediatric and congenital heart surgery: a narrative review. Regen Med Rep. 2024;1(2):131-136.

Introduction

Pediatric and congenital heart surgery is a highly specialized field requiring complex decision-making to analyse all dynamic factors involved and requires close collaboration among different members of various teams. The advent of artificial intelligence (AI) and machine learning offers significant opportunities to enhance various aspects of this field. Machine learning, which is a key subset of AI, utilizes algorithms learning from existing datasets to identify patterns, make predictions, and ultimately improve outcomes. This process typically involves several stages, including data preprocessing, model training, and validation by utilising a separate subset of data to assess its own accuracy and generalisability. These technologies facilitate more accurate data-driven decision-making compared to traditional evidence-based medicine. Moreover, deep learning, a subset of machine learning utilizing artificial neural networks for intricate tasks such as image classification, natural language processing, and reinforcement learning, holds significant promise for enhancing diagnostic accuracy and treatment approaches in pediatric and congenital heart surgery.

Despite the promising potential of AI already proven in other aspects within the field of cardiology, including the use of diagnostic methodologies[1] and the treatment of arrhythmias,[2] its application in pediatric and congenital heart surgery is still in its infancy. This is most probably due to the huge variety of congenital heart defects with more than 700 different diagnoses,[3] many with a spectrum of morphological and pathophysiological presentations, with the consequence of more than 3000 surgical options available, and the extreme variability of indications based on the surgical and institutional experiences, local facilities and resources, and socio-economic factors.[3]

The large number of data derived from the multiple diagnoses, indications, procedures, genetic etiology etc. makes the preparation of AI protocols within pediatric and congenital heart surgery very challenging. To date, there exists no centralised database which comprehensively integrates the vast array of data generation from such operations. Current databases including the European Congenital Heart Surgery Association, the Society of Thoracic Surgeons Congenital Heart Surgery Database, and the database of the World Society of Pediatric and Congenital Heart Surgery, are all valuable, but they tend to be limited by several factors including variability in data entry, inconsistent and lack of reporting standards, limited validation of the acquired data, surgical outcomes limited to the early follow-up, incomplete data sets for a comprehensive analysis. These databases often focus on specific geographic regions or healthcare systems, leading to fragmentation of information and limiting the ability to conduct global comparisons of surgical outcomes. AI offers a promising solution to these challenges by the use of predictive modelling, creating a completer and more usable dataset for clinical and research purposes. Surgeons could access real-time data on early and late outcomes, incidence and type of complications, and best practices from around the world, enhancing both clinical decision-making and research. AI and machine learning algorithms have been identified to be more accurate in predicting mortality and graft failure after heart transplantation compared to traditional scoring systems and conventional regression analysis.[4]

In pediatric and congenital heart surgery, AI could play a transformative role in pre-operative planning, peri-operative decision-making, and post-operative care. Predictive algorithms could assist in selecting the most appropriate operative technique for a specific defect based on historical data from hundreds of thousands of similar cases. In the future, the integration of AI into pediatric and congenital heart surgery could not only lead to optimal patient outcomes, but also provide crucial tools for education and training, helping to bridge the gap in expertise, particularly in low-income countries. AI simulations can recreate complex operations in a virtual environment, allowing surgeons in resource-constrained environments to practice and refine their skills without the need for extensive physical resources. These models can provide real-time feedback and adapt to various operative scenarios, aiding surgeons prepare for more rare or challenging cases.[5, 6]

This review seeks to explore the potential utilisation of AI in pediatric and congenital heart surgery to facilitate the decision-making processes particularly in complex and rare cases, and also as a machine learning tool, including its integration into modern teaching modalities, and its role in overcoming geographic barriers in low-income countries.[7-12] Additionally, the review examines the use of AI in analyzing the various available pediatric and congenital heart defects databases and addressing their limitations.

Literature Search Strategies

A thorough search of electronic databases including PubMed, Scopus, Google Scholar and Cochrane, was conducted to identify relevant literature. The search terms included "artificial intelligence," "congenital heart surgery," "pediatric cardiac surgery," "machine learning," "decision-making," "multidisciplinary teams," "databases," "surgical training," and "teaching modalities."

All the relevant articles were selected based on their focus on AI applications in pediatric and congenital heart surgery. Only articles published with full text in English language were included, excluding articles published in any other language, even if the abstract was translated in English.

Artificial Intelligence and Outcome Prediction

Characteristics of source of evidence

AI has already shown good evidence for predicting the diagnosis of congenital heart defects with the present limitations of two-dimensional (2D) fetal cardiac imaging techniques.[13] While traditional 2D echocardiograms provide limited perspectives, AI can analyse three-dimensional (3D) volumetric data, thus offering a comprehensive view of the heart's structure. This capability allows for the detection of subtle abnormalities that may be overlooked in 2D images without the need for more expensive or invasive imaging methodologies. Moreover, AI demonstrated superior capabilities in pattern recognition through the application of convolutional neural networks trained on extensive datasets comprising both normal and pathological cardiac images. Convolutional neural networks are a class of deep learning, algorithms which can process grid structures including images by applying filters to detect features and pattern to automatically detect and learn hierarchical features and patterns. This framework enables multiple levels of understanding; where lower layers detect basic features such as edges and textures, whilst higher layers combine these features into more complex representations. This process enhances the model's ability to identify subtle structural abnormalities that may confuse human operators. This technology has been applied within various fields in the care of congenital cardiac malformations, including AI-assisted auscultations for detecting congenital heart defects[14] and machine learning for blood test analysis in pulmonary artery hypertension phenotype testing.[15]

Within pediatric and congenital heart surgery, nonlinear models for predicting post-operative outcomes demonstrate a significant advancement in risk assessment. For example, traditional pre-operative risk assessment tools often assume a linear interaction between the risk factors. This does not consider the complex and inter-connected nature of a patient's condition whereby various risk factors interact with each other dynamically. Machine learning frameworks, specifically optimal classification trees, are a type of decision tree model designed to analyse substantial datasets by dividing the data into subsets based on the most significant predictors. Optimal classification trees enhance interpretability and accuracy by identifying nonlinear patterns and interactions. This allows for a more holistic understanding of how multiple factors contribute to patient outcomes.

Critical appraisal of results of evidence

AI can enhance surgical decision-making by offering data-driven insights during the peri-operative period that surgeons may overlook if deemed not clinically relevant. For example, data on post-heart transplant immunosuppression is seldom collected because it was traditionally viewed as not having a key role in influencing mortality. However, a machine learning algorithm identified that a patient's immunosuppressive regimen plays a significant role in predicting graft failure.[16] By assessing a complete dataset rather than relying solely on what is generally deemed clinically relevant, AI can enhance our understanding of various determinants in patient outcomes.

By leveraging large datasets, optimal classification trees can detect these intricate relationships that traditional models might overlook with recent models showing superior predictive power to traditional regression analysis as verified with the Aristotle Complexity Score.[17] These models can help the surgeon identify high-risk patients pre-operatively with a higher degree of accuracy to promote informed decision-making and resource optimization, considering that a surgical approach can have dozens of variations within each step of the same operation.

Examples of results based on evidence

For instance, "functionally" single ventricle can have a huge spectrum of morphological features, range from underdevelopment of the left ventricle, like in hypoplastic left heart syndrome to underdevelopment of the right ventricle, as in pulmonary atresia with intact ventricular septum. This heterogeneous nature complicates the prediction of the details of each operative intervention as well as the long-term outcomes. As such, AI and machine learning could represent a promising solution for improving prognostic predictions. Future advancements in AI could possibly facilitate the development of personalised risk assessment tools considering not only the anatomical and pathophysiological characteristics of each patient, but also including genetic and environmental factors.

Additionally, traditional models often rely on limited survival analyses that do not extend beyond infancy, which can hinder effective decision-making for families and healthcare providers for complex heart malformations requiring staged repair from early infancy to late teenage years. Studies utilising AI to incorporate data from various phases of care over time showed promising results in predicting transplant-free survival for patients with hypoplastic left heart syndrome.[18] By investigating individual patient trajectories, such models can help tailor interventions to the individual patients more precisely, and in a timely manner. However, it is essential to exercise caution against over-reliance on algorithmic prediction as this may encourage deterministic thinking which could overshadow the role of experience-based clinical judgement of specific surgeon and their institutions. Ultimately, the goal of the integration of AI into clinical practice should enhance, rather than replace, our understanding and treatment of complex congenital heart defects.

Surgical Decision-Making

Surgical decision-making in pediatric and congenital heart surgery is a complex process requiring the integration of various peri-operative clinical factors and could be further enhanced using AI. For example, the right ventricular function is rarely monitored during congenital heart surgery due to the peculiar anatomy and the lack of an accomplished intra-operative monitoring. However, by utilising AI driven epidermal kinematics for live intra-operative videos, algorithms can recognise dynamically abnormal anatomical and functional features, allowing for timely interventions before chest closure.[19]

Further examples of evidence

AI systems can also provide real-time guidance and decision support intra-operatively by integrating intra-operative imaging, physiological data, and predictive modelling. These AI algorithms can offer dynamic, data-driven insights during critical stages of the procedure. For example, real-time AI analysis of intra-operative echocardiography can highlight subtle anatomical variations that might otherwise go unnoticed.[20] The integration of AI into surgical decision-making has the potential to transform the complexity of pediatric and congenital heart surgery into more manageable, data-enhanced processes.

It is important to highlight that although AI remains promising in enhancing, not replacing, surgical decision-making, there are limitations existing in its routine implementation. Obstacles may include, but they are not limited to privacy concerns, algorithmic biases, and data scarcity. All these must be overcome, tested and validated prior to any regular deployment in the operating room.[21] AI models trained on specific datasets may not be generalizable to all patient populations and/or clinical situations.[22] For example, AI systems trained primarily on data from high-resourced hospitals may perform poorly in settings with fewer resources, different facilities, or more complex patient characteristics. Addressing these biases and ensuring broad generalization across different surgical contexts is critical for safe routine utilization.

Utilization of Databases

The utilization of databases is critical for advancing AI applications in pediatric and congenital heart surgery. Current databases, such as the European Congenital Heart Surgery Association, the Society of Thoracic Surgeons Congenital Heart Surgery Database, and the database of the World Society of Pediatric and Congenital Heart Surgery, contain valuable information but are often hindered by inconsistencies in data entry and reporting standards. Additionally, the fragmentation of information across various regional and institutional databases restricts the ability to conduct comprehensive analyses and comparisons of surgical outcomes at a global scale. Machine learning models can integrate heterogeneous data from various sources, including hospital electronic health records and known surgical databases, while preserving data integrity.[23]

Existing surgical databases are increasingly being used to inform the design of future clinical trials. By utilising this data, AI can predict clinical outcomes with greater accuracy to allow researchers to tailor trials more specifically to patient subgroups rather than relying on broad general populations.[24] This approach not only improves the relevance of clinical trials but also reduces the statistical variability that can often skew trial results. Utilising an AI algorithm to predict participant outcomes and identify those who are likely to progress rapidly and achieve trial endpoints sooner could result in shorter trial durations.[25] This is crucial in pediatric and congenital cardiac surgery where the complexity and variability of conditions make it challenging to design one-size-fits-all trials. By identifying subgroups that are likely to respond similarly to certain interventions, clinical trials can be more focused for our younger patient cohort.

However, due to the lack of a global centralized database and no formal data repository for pediatric and congenital cardiac surgery, the relatively low volume of data presents a significant challenge for developing reliable AI models. The complexity and heterogeneity of congenital heart defects, the limited amount of data collected and available, complicates the possibility of any meaningful analysis representing the malformation breadth and impact on the patients. To address the small sample sizes commonly encountered in congenital heart defects, studies have employed synthetic data generation to create large datasets from limited original data despite the introduction of modelling bias.[26]

In the context of global pediatric and congenital cardiac surgery, AI can integrate surgical databases from low-income countries with high income countries, and therefore facilitate international collaboration to allow for the sharing of knowledge and outcomes. This integration can bridge the gap between regions, allowing for a more comprehensive understanding of best practices and improving surgical care worldwide. Ultimately, these barriers can only be overcome with a concerted effort to establish a global congenital pediatric and cardiac surgery database. Such a database would facilitate robust analyses that can inform best practices, improve patient care, and enhance the development of predictive models.

Surgical Education and Training

AI's potential role in surgical education and training is particularly relevant in low-income countries, where access to specialized training can be limited. AI-driven simulations and virtual reality tools have been shown to provide effective training environments for surgeons.[27] As the complexity of surgical techniques for congenital heart defects continue to evolve, AI tools can assist in streamlining the learning process by utilizing adaptive learning algorithms to tailor educational content to surgical trainees, based on their individual performance, pace, and specific areas of difficulty.[28] By analysing interaction data, these algorithms can identify knowledge gaps and dynamically adjust the curriculum, ensuring that all surgical trainees receive a personalized training experience maximising their learning outcomes.

There has been a large emphasis recently on training with 3D silicon congenital heart defects model to allow trainees and caregivers to better understand the complexity of the anatomy involved. AI-driven augmented reality can utilise deep learning algorithms to create highly realistic surgical scenarios.[29-31] This approach offers trainees a more realistic experience of a safe environment, allowing trainers to simulate the conditions of an operating room, where simulators can respond to each incision and suturing in real time.

Minimally invasive pediatric and congenital cardiac surgery in particular face challenges specific to steep learning curves and often rely on observational learning with varying assessment quality.[32] Video-labelling could be utilized to automatically identify and categorize the critical phases of the most complex procedures to allow trainees and surgeons to review intra-operatively key moments more efficiently.34 Video-labelling can significantly therefore enhance the training process, ensuring that learners focus on the most relevant aspects of the procedure, thus improving skill acquisition and surgical outcomes.[33]

Limitations

This review is missing rigorous and systematic validation of the AI models presented. The cases reported from the literature are limited in scope and are not backed by multicenter clinical trials, therefore reducing the robustness of the presented results. Furthermore, the review provides limited insights into the integration of AI into current clinical workflows, which should be crucial for practical implementation.

The main reason behind these limits is the relatively reduced number of surgical cases suitable for the introduction of AI approach in daily clinical practice, in addition to the constant need for screening and reporting the outcomes, not yet compulsory in all countries.

On the other side, the importance of the role of AI and machine learning in all aspects of regenerative medicine relative to congenital heart defects is confirmed by the huge number of publications appearing in the literature in the very few weeks period between the submission of our original manuscript and the end of the review process.[34-45]

Conclusions

The application of AI in regenerative medicine related to pediatric and congenital heart surgery holds great promise across various domains including peri-operative decision-making, monitoring of surgical outcomes, enhancing surgical education and improving care for congenital heart defects in low-income countries. While challenges exist in the implementation of AI in the current landscape, its ongoing evolution present a promising pathway to bridging gaps in care, particularly for vulnerable populations in resource constrained environments.

Author contributions

Data collection and analysis, preparation of the manuscript, final approval before submission: JF. Review and approval of the manuscript, final approval before submission: JG. Discussions about the topic of the review, review of the manuscript, and final approval before submission: EP. Proposal of the topic for review, work on the text of the manuscript, preparation and final approval before submission: AFC.

Conflicts of interest

We have no competing interests to disclose.

Editor note: AFC is an Editorial Board Member of *Regenerative Medicine Reports*. The article was subject to the journal's standard procedures, with peer review handled independently of this Editorial Board Member and their research groups.

Data availability statement

Not applicable.

Open access statement

References

1. Sun X, Yin Y, Yang Q, Huo T. Artificial intelligence in cardiovascular diseases: diagnostic and therapeutic perspectives. *Eur J Med Res*. 2023;28:242.
2. Nagarajan VD, Lee SL, Robertus JL, Nienaber CA, Trayanova NA, Ernst S. Artificial intelligence in the diagnosis and management of arrhythmias. *Eur Heart J*. 2021;42:3904-3916.
3. Mavroudis C, Jacobs JP. Congenital heart surgery nomenclature and database project: overview and minimum dataset. *Ann Thorac* Surg. 2000;69:S2-17.
4. Naruka V, Rad AA, Ponniah HS, et al. Machine learning and artificial intelligence in cardiac transplantation: A systematic review. *Artif Organs.* 2022;46:1741-1753.
5. Bhargava H, Salomon C, Suresh S, et al. Promises, pitfalls, and clinical applications of artificial intelligence in pediatrics. *J Med Internet Res*. 2024;26:e49022.
6. Jha AK, Kickbusch I, Taylor P, Abbasi K. The lancet commission on ai in health. *Lancet*. 2019;394:1371-1372.
7. Arksey H, O'Malley L. Scoping studies: towards a methodological framework. *Int J Soc Res Method*. 2005;8:19-32.

8. Chen JH, Asch SM, Elmore JG. Machine learning and prediction in medicine: beyond the peak of inflated expectations. *New Engl J Med*. 2021;383:66-72.
9. Esteva A, Robicquet A, Ramsundar B, et al. A guide to deep learning in healthcare. *Nat Med*. 2019;25:24-29.
10. Gholami B, Haddad WM, Tannenbaum AR. Realtime machine learning modelling for COVID-19 data. *Sci Rep*. 2019;11:1-12.
11. Kim HG, Kim HM, Park JH. Machine learning approaches for stroke prediction in patients with atrial fibrillation. *J Am Heart Ass*. 2021;10:e019036.
12. Liu W, Zhang W, Zhang W, Chen Z. A machine learning model for predicting the risk of congenital heart defects in the Han Chinese population. *Front Genet*. 2020;11:156.
13. Garcia-Canadilla P, Sanchez-Martinez S, Crispi F, Bijnens B. Machine learning in fetal cardiology: what to expect. *Fetal Diagn Ther*. 2020;47:363-372.
14. Lv J, Dong B, Lei H, et al. Artificial intelligence-assisted auscultation in detecting congenital heart disease. *Eur Heart J Digit Health*. 2021;2:119-124.
15. Sweatt AJ, Hedlin HK, Balasubramanian V, et al. Discovery of distinct immune phenotypes using machine learning in pulmonary arterial hypertension. *Circ Res*. 2019;124:904-919.
16. Agasthi P, Buras MR, Smith, SD, et al. Machine learning helps predict long-term mortality and graft failure in patients undergoing heart transplant. *Gen Thorac Cardiovasc Surg.* 2020;68:1369-1376.
17. Bertsimas D, Zhuo D, Dunn J, et al. Adverse outcomes prediction for congenital heart surgery: a machine learning approach. *World J Pediatr Congenit Heart Surg*. 2021;12:453-460.
18. Smith AH, Gray GM, Ashfaq A, Asante-Korang A, Rehman MA, Ahumada LM. Using machine learning to predict five-year transplant-free survival among infants with hypoplastic left heart syndrome. *Sci Rep*. 2024;14:4512.
19. Lo Muzio FP, Rozzi G, Rossi S, et al. Artificial Intelligence supports decision making during open-chest surgery of rare congenital heart defects. *J Clin Med*. 2021;10:5330.
20. Al'Aref SJ, Anchouche K, Singh G, et al. Clinical applications of machine learning in cardiovascular disease and its relevance to cardiac imaging. *Eur Heart J.* 2019;40:1975-1986.
21. Esmaeilzadeh P. Challenges and strategies for wide-scale artificial intelligence (AI) deployment in healthcare practices: A perspective for healthcare organizations. *Artif Intell Med*. 2024;151:102861.
22. Nazer LH, Zatarah R, Waldrip S, et al. Bias in artificial intelligence algorithms and recommendations for mitigation. *PLOS Digit Health.* 2023;2:e0000278.
23. Martínez-García M, Hernández-Lemus E. Data Integration Challenges for Machine Learning in Precision Medicine. *Front Med (Lausanne).* 2022;8:784455.
24. Sangari Y, Qu Y. A Comparative Study on Machine Learning Algorithms for Predicting Breast Cancer Prognosis in Improving Clinical Trials. 2020 International Conference on Computational Science and Computational Intelligence (CSCI), Las Vegas, NV, USA; 2020:813-8182.
25. Lee CS, Lee AY. How artificial intelligence can transform randomized controlled trials. *Transl Vis Sci Technol.* 2020;9:9.
26. Diller GP, Vahle J, Radke R, et al. Utility of deep learning networks for the generation of artificial cardiac magnetic resonance images in congenital heart disease. *BMC Med Imaging*. 2020;20:113.
27. Park JJ, Tiefenbach J, Demetriades AK. The role of artificial intelligence in surgical simulation. *Front Med Technol*. 2022;4:1076755.
28. Sewell C, Morris D, Blevins NH, et al. Providing metrics and performance feedback in a surgical simulator. *Comput Aided Surg*. 2008;13:63-81.
29. Wang DD, Qian Z, Vukicevic M, et al. 3D Printing, computational modelling, and artificial intelligence for structural heart disease. *JACC Cardiovasc Imaging*. 2021;14:41-60.
30. Biglino G, Capelli C, Konlordou D, et al. Use of 3D models of congenital heart disease as an education tool for cardiac nurses. *J Congenit Heart Dis.* 2017;12:113-118.
31. Loke YH, Harahsheh AS, Krieger A, Olivieri LJ. Usage of 3D models of tetralogy of Fallot for medical education: impact on learning congenital heart disease. *BMC Med Educ.* 2017;17:54.
32. Dodge-Khatami J, Dodge-Khatami A, Nguyen TD, Ruffer A. Minimal invasive approaches for pediatric and congenital heart surgery: safe, reproducible, more cosmetic than through sternotomy, and here to stay. *Trans Pediatr*. 2023;12:1744-1752.
33. Brian R, Murillo A, Gomes C, Alseidi A. Artificial intelligence and robotic surgical education. Global Surg Educ. 2024. doi.org/10.1007/s44186-024-00262-5.
34. Jia H, Tang S, Guo W, et al. Differential diagnosis of congenital ventricular septal defect and atrial septal defect in children using deep learning-based analysis of chest radiographs. *BMC Pediatr.* 2024;24:661.
35. Chen SH, Weng KP, Hsieh KS, et al. Optimizing object detection algorithms for congenital heart diseases in echocardiography: exploring bounding box sizes and data augmentation techniques. *Rev Cardiovasc Med*. 2024;25:335.
36. Papunen I, Ylanen K, Lundqvist O, et al. Automated analysis of heart sound signals in screening for structural heart disease in children. *Eur J Pediatr.* 2024;183:4951-4958.
37. Mayer PJ, Poyraz RA, Holter T, Thun S, Vorisek CN. Data for AI in congenital heart defects: systematic review. *Srud Health Technol Inform*. 2024;316:820-821.
38. Jain SS, Elias P, Clark DE. Democratizing congenital heart disease management: the potential for AI-enabled care and necessary future directions. *J Am Coll Cardiol*. 2024;84:829-831.
39. Maayourian J, Gearhart A, La Cava WG, et al. Deep learning-based electrocardiogram analysis predicts biventricular dysfunction and dilatation in congenital heart disease. *J Am Coll Cardiol.* 2024;84:815-828.
40. Kong F, Stocker S, Choi PS, Ma M, Ennis DB, Marsden AL. SDF4CHD: Generative modeling of cardiac anatomies with congenital heart defects. *Med Image Anal*. 2024;97:103293.
41. Chinni BK, Manlhlot C. Emerging analytical approaches for personalized medicine using machine learning in pediatric and congenital heart disease. *Can J Cardiol.* 2024;40:1880-1896.
42. Yu L, Yu Y, Li M, et al. Deep learning reconstruction for coronary CT angiography in patients with origin anomaly, stent or bypass graft. *Radiol Med*. 2024;129:1173-1183.
43. Lu Y, Tan G, Pu B, et al. SKOC: a general semantic-level knowledge guided classification framework for fetal congenital heart disease. *IEFE J Biomed Heatlh Inform*. 2024;28:6106-6116.
44. Pace DF, Contreras HTM, Romanowicz J, et al. HVSMR-2.0: A 3D cardiovascular MR dataset for whole-heart segmentation in congenital heart disease. *Sci Data*. 2024;11:721.
45. Drukker L. The Holy Grail of obstetric ultrasound: can artificial intelligence detect hard-to-identify fetal cardiac anomalies? *Ultrasound Obstert Gynecol.* 2024;64:5-9.

Date of submission: October 8, 2024
Date of decision: November 10, 2024
Date of acceptance: December 6, 2024
Date of web publication: December 20, 2024