

Recent Surgical Advances in the Management of Congenital Heart Disease: A Narrative Review

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ABSTRACT

Congenital Heart Disease (CHD) remains the most common cause of death due to congenital disabilities. The number of adults with CHD is rapidly growing, even though it is still the primary cause of morbidity and mortality in children. Various treatments for different types of CHD are currently available in the literature. Over recent decades, surgical management has undergone a transformative shift, driven not only by refined techniques but also by the integration of hybrid procedures, simulation technologies, and precision-based planning. The current review summarises major recent advances in valve-sparing repair techniques, hybrid neonatal strategies, 3D-printed surgical simulation, AI-based imaging guidance, and robotic-assisted congenital cardiac surgery. These innovations collectively show a clear shift towards more precise, less invasive, and outcome-driven management of complex CHD. The present review highlights key advancements in surgical approaches to CHD, from early neonatal repairs to robotic-assisted and imaging-guided innovations, offering a forward-looking perspective on how modern tools are reshaping outcomes for complex cardiac lesions.

Keywords: Artificial intelligence, Heart defects, Hybrid cardiac procedures, Paediatric cardiac surgery, Robotic surgery, Three-dimensional printing

INTRODUCTION

One of the most common congenital conditions, Congenital Heart Disease (CHD), affects between 0.8% and 1.2% of live births globally [1]. Few patients with moderate to severe CHD lived to adulthood a few decades ago [2]. Although CHD remains the most common cause of death due to congenital disabilities, most patients can now survive into childhood, even those with severe cardiac defects like Hypoplastic Left Heart Syndrome (HLHS) [2].

Defects in CHD range widely, from simple malformations with a good prognosis to more complicated and severe lesions that necessitate numerous catheter-based or surgical procedures with unpredictable long-term results. The number of adults with CHD is rapidly growing, even though it is still the primary cause of morbidity and mortality in children [3]. As a result of significant advancements in disease recognition and better medical and surgical management throughout life, over 90% of children with CHD now live to adulthood [3]. CHD included various structural defects, including Atrial Septal Defect (ASD), Ventricular Septal Defect (VSD), Tetralogy of Fallot (TOF), Truncus Arteriosus (TA), Coarctation of the Aorta (CoA), Transposition of the Great Arteries (TGA), as well as others [3].

Medical and surgical procedures are just two of the many techniques used to treat CHD. Patients may be prescribed medication to manage their symptoms, prevent complications, and improve overall cardiac function. Since CHD is a structural defect, surgical intervention is another method that is more frequently used. Open-heart surgery, minimally invasive surgery, endovascular procedures, and hybrid procedures have all been made possible by numerous advancements in the treatment of CHD [4,5]. Various treatments for different types of CHD are currently available in the literature [2]. Diuretics, Angiotensin-Converting Enzyme (ACE) inhibitors, beta-blockers, prostaglandin E1 for duct-dependent lesions, and antiarrhythmic drugs are frequently used in CHD treatment. Surgical options include ASD/VSD closure, arterial switch operation, valve-sparing TOF repair, and staged procedures like Glenn and Fontan for single-ventricle physiology. These interventions have significantly improved the survival and long-term outcomes of children with CHD [2].

A study providing recent interventions and surgical outcomes for different types of CHD should be available to offer readers a general overview of treatment options and outcomes. The present review aimed to summarise recent advancements in the surgical and technology-assisted management of CHD to support clinical decision-making and improve understanding of emerging therapeutic strategies.

MATERIALS AND METHODS

A narrative literature review was conducted using PubMed, Scopus, Google Scholar, and Web of Science databases for studies published between 2000 and 2025. Keywords included 'congenital heart disease', 'arterial switch operation', 'hybrid cardiac surgery', '3D printing', 'robotic surgery', and 'artificial intelligence in congenital heart disease'. Relevant English-language studies, systematic reviews, meta-analyses, observational studies, and landmark surgical reports were included based on relevance to recent advances in congenital cardiac surgery.

Inclusion criteria: Original research articles, systematic reviews, meta-analyses, multicentre studies, and landmark English-language surgical reports were included. Studies addressing recent surgical techniques, hybrid interventions, imaging-guided planning, and technology-assisted congenital cardiac procedures were considered eligible.

Exclusion criteria: Duplicate studies, non-English publications, conference abstracts without full text, and articles with limited clinical relevance were excluded. Eligible studies were screened based on title, abstract, methodological relevance, and applicability to contemporary congenital cardiac surgery.

A Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA)-style approach for literature identification and screening was followed to improve transparency in study selection; however, formal systematic review registration and quantitative meta-analysis were not performed due to the narrative nature of the review.

CLASSIFICATION OF CONGENITAL HEART DISEASES

Congenital heart diseases are a broad group of structural anomalies found during birth that affect the heart and great vessels. These are classified into 2 categories: acyanotic and cyanotic defects. This classification is based upon the presence or absence of cyanosis, which occurs due to inadequate arterial blood oxygenation. Acyanotic CHD has left-to-right shunting of blood, which leads to increased pulmonary blood flow but maintains systemic oxygen saturation. Breathlessness, recurrent respiratory chest infections without cyanosis, is the usual presentation for this type of defect. ASD, VSD, PDA, and CoA are common acyanotic CHD [6].

Cyanotic type of CHD has right-to-left shunting or parallel circulation systems that bypass the lungs, causing visible cyanosis due to desaturation. These defects are usually seen in the neonatal period with findings of central cyanosis, poor feeding, and failure to thrive. TOF, TGA, tricuspid Atresia, truncus arteriosus, Total Anomalous Pulmonary Venous Return (TAPVR), and HLHS are common cyanotic CHD. Elective surgeries, catheter-based interventions can be performed in early childhood and infancy for acyanotic defects, depending upon the severity of the defect. The small ASD may close spontaneously, but the large VSD requires surgical closure. The neonates born with cyanotic heart defects often need immediate or staged surgical procedures, usually starting in the first few days or weeks of birth, to improve oxygen levels and support survival. A complete repair or a preliminary Blalock-Taussig shunt is required for TOF, and HLHS requires a multistage approach such as the Norwood-Glenn-Fontan sequence [7,8]. Summary of the classification for CHD is shown in [Table/Fig-1].

Classification	Types	Examples	Surgical relevance
Physiological	Acyanotic	ASD, VSD, PDA, CoA	Usually managed by elective catheter-based or surgical repair depending on defect size and symptoms
	Cyanotic	TOF, TGA, HLHS, TAPVR, Truncus arteriosus	Require urgent or staged neonatal surgical correction to restore systemic oxygenation
Anatomical	Septal defects	ASD, VSD	Patch/device closure
	Outflow tract defects	TOF, Truncus arteriosus	RVOT reconstruction, valve-sparing or transannular patch repair
	Valvular defects	Pulmonary stenosis, Aortic stenosis	Balloon valvotomy or valve repair
	Vascular anomalies	CoA, TAPVR	Resection, anastomosis, stenting or rerouting of pulmonary veins
Complexity-based (ACC/AHA)	Simple	ASD, small VSD, PDA	Usually single-stage repair
	Moderate	TOF, CoA	Require specialised paediatric cardiac surgery
	Great complexity	HLHS, Single ventricle, TGA	Multistage palliation (Norwood-Glenn-Fontan)

[Table/Fig-1]: Summary of the classification for CHD.

ASD: Atrial septal defect; VSD: Ventricular septal defect; PDA: Patent ductus arteriosus; CoA: Coarctation of aorta; TOF: Tetralogy of Fallot; TGA: Transposition of great arteries; HLHS: Hypoplastic left heart syndrome; TAPVR: Total anomalous pulmonary venous return; ACC/AHA: American College of Cardiology/American Heart Association

TIMING OF SURGICAL INTERVENTION IN CHD

The optimal timing for treatment in CHD depends upon creating a balance between the urgency of treatment and the relative risks.

Neonatal Period for Cyanotic/Critical Lesions

The Arterial Switch Operation (ASO) are most effective for TGA if performed within the first week after birth [9]. A study that included

1005 neonates had a median repair age of 6 days; this was associated with an increase in complications and higher treatment costs [10]. The European registry data reports a median timing of around 3 to 4 weeks, which shows system-level delays or late referrals rather than the strategy that should ideally be preferred. Early neonatal repair remains critical to maximise left ventricular efficiency and reduce post-operative complications [11].

The ductal-dependent lesions, such as obstructed TAPVR, Hypoplastic or Tricuspid Atresia, and CoA, require surgical correction within the first few days or weeks of birth to restore pulmonary and systemic circulation [11].

Infancy: Definite and Palliative Repairs

The elective repair for TOF is usually recommended between 3 and 6 months after birth. In the presence of persistent cyanosis, early repair or shunting is considered vital [11]. To prevent worsening of AV valve regurgitation and volume overload, a complete repair is recommended within 4 to 6 months for AVSD [11]. The large VSD and PDA have a significant left-to-right shunting, to avoid pulmonary hypertension and the ongoing heart failure, surgical closure is recommended between 3 and 12 months, depending upon the complexity and presentation of the child [9].

Staged Repairs for Single-ventricle Lesions

The HLHS, tricuspid atresia, or double inlet left ventricle are complex CHD with single ventricle physiology; staged repairs are considered for such cases [11]. Biventricular repairs are not adaptable for these lesions; they advance through a three-stage pathway that concludes with a Fontan-type circulation. The Norwood procedure creates a neo-aorta using the pulmonary artery and establishes pulmonary blood flow by a shunt (BT shunt or Sano modification), leading to reconstruction of systemic outflow. It is usually performed within 1 to 2 weeks after birth [12]. The bidirectional Glenn or hemi-fontan redirects the superior vena cava to the pulmonary arteries, offloading the single ventricle and improving the systemic oxygen levels [13]. It is usually performed between 4 and 6 months after birth. The Fontan completion connects the inferior vena cava to the pulmonary circuit and completes the total Cavo-pulmonary connection. It is done between 2 and 4 years of age, but it has long-term complications such as protein-losing enteropathy, liver fibrosis and arrhythmias [14].

Impact of Timing on Outcomes

The study by EuroLINKCAT analysed more than 6000 infants across 13 European countries, found the median age of first surgery to be 3.6 weeks, and a 30-day post-operative mortality rate of 6%. The disparity is not a sign of clinical indecision, but instead of disparities in healthcare infrastructure, diagnostic delays, and access to specialised surgical centres [11]. Compared to later timing, the early ASO before 8 days of age is associated with a lower composite morbidity, a prolonged ICU stay, and reoperation [10]. According to a study conducted on over 2500 neonates, non emergent cardiac surgeries performed between 2 and 7 days of age result in comparable outcomes to those performed later in neonatal development. However, the length of hospitalisation may be greater for older neonates [15].

RECENT ADVANCES IN SURGICAL TECHNIQUES FOR CHD

Refinements in Surgical Techniques

Arterial switch operation: The ASO is a critical surgical intervention for correcting CHD, particularly TGA. This procedure has shown promising outcomes, especially in paediatric patients with complex CHD and severe Pulmonary Hypertension (PH). The following sections outline the key aspects of ASO in the context of CHD. ASO is primarily indicated for TGA and related anomalies, such

as the Taussig-Bing anomaly, particularly in children older than six months with acceptable pulmonary arterial resistance. Successful outcomes are contingent upon the patient's condition, specifically the absence of severe cyanosis ($\text{SaO}_2 > 60\%$) and manageable pulmonary arterial resistance [16].

A study by Liu Y et al., evaluated 23 consecutive paediatric patients. These patients suffered from complex CHD, including TGA and Taussig-Bing anomaly. All patients underwent the ASO. Post-operatively, the pulmonary pressure significantly decreased to 23 ± 9 mmHg. Among them, 20 children survived the ASO. The study concluded that ASO can achieve satisfactory early results for children older than 6 months with complex congenital heart defects and moderate to severe PH [16].

A study by Xu Z et al., reports on 61 complex congenital heart disease patients undergoing arterial switch operation. In all patients, the cyanosis disappeared, and the physical activities improved significantly. The effect of the arterial switch operation on the treatment of TGA was well accepted in this study. The procedure used in treating Taussig-Bing can prevent pulmonary obstruction and avoid the complication of left ventricular outflow tract obstruction caused by intraventricular repair [17]. Follow-up studies indicate that patients experience sustained improvements in heart function, with no significant complications reported in the months following surgery.

Valve-sparing repair in TOF: Valve-sparing repair in TOF has emerged as a promising alternative to Traditional Transannular Patch (TAP) techniques, primarily to preserve pulmonary valve function and reduce long-term complications. This approach involves techniques such as skeletonising the pulmonary annulus, which helps maintain valve integrity while alleviating right ventricular outflow tract obstruction. A study by Raju V et al., found that 390 patients had total repair of TOF; the mid-term outcomes on the status of the pulmonary valve gradient, degree of pulmonary regurgitation, reintervention rate, and mid-term survival after PVSR were investigated. All patients had a pulmonary valve Z score of > -2.5 . The post-repair mean RV/LV pressure ratio was 0.49 ± 0.12 . There was no surgical mortality. Pulmonary valve-sparing repair gives good mid-term outcomes in a specific group of patients with TOF. Reintervention rates are very low, and most patients' peak gradient across the pulmonary valve came down during mid-term follow-up [18].

A meta-analysis in 2024 involving 11,723 patients across 40 studies concluded that in several critical perioperative outcomes, VS repairs performed noticeably better than TAP. The cardiopulmonary bypass time was reduced by 15 minutes, shortened and Intensive Care Unit (ICU) stay by about 0.7 days, total hospital stay to 2.3 days, ventilation time decreased by 15 hours, and mortality was halved, along with reduced risk of pulmonary regurgitation [19].

A Valve-sparing (VS) approach can lead to mild pulmonary stenosis if the annulus size is small. In a study, intraoperative balloon dilation with Valve-sparing with Intraoperative Balloon Dilation (VS-IBD) in 139 patients showed similar outcomes to TA. VS-IBD was associated with low but higher early reintervention rates compared to TAP, but less adverse RV remodelling. Over half of the patients were without significant PR or PS at mid-term follow-up [20].

Staged and Hybrid Approaches

Hybrid norwood procedure for Hypoplastic Left Heart Syndrome (HLHS): The hybrid Norwood procedure is a treatment approach for patients with HLHS. It combines bilateral pulmonary artery banding and ductal stenting. This reduces the surgical risks and supports staged palliation in selected patients with HLHS. In a case report by Cassanello P a multidisciplinary team determined that a term newborn with a slight aortic arch, hypoplastic left heart, ASD, and Total Anomalous Pulmonary Venous Connection (TAPVC) qualified for a hybrid palliation on day six following TAPVC surgery. On day

eleven of life, two Sinus Superflex-DS stents were subsequently implanted percutaneously as ductal stents. The study concluded that, for HLHS, the hybrid approach has shown itself to be a safe substitute for the Norwood procedure [21].

A meta-analysis by Cao J et al., compared hybrid and Norwood procedures for HLHS. Patients who received the hybrid procedure had a significantly higher early mortality rate than those who received the conventional Norwood procedure. The early mortality Relative Risk (RR) in hybrid patients was 1.54. Hybrid patients had a lower transplant-free survival rate at six months and one year. More reinterventions were necessary for hybrid patients after their initial surgical palliation. Both groups experienced similar lengths of hospital and ICU stay after surgery, despite differences in mortality and reinterventions. Research indicates that compared to the conventional Norwood procedure, the hybrid procedure is linked to a lower early survival rate when used for initial palliation in infants with HLHS [22].

Hybrid periventricular Ventricular Septal Defect (VSD) closure:

Hybrid periventricular VSD closure is a combination of a minimally invasive technique with potential for immediate conversion to open heart surgery, if required. This technique has given potential results in terms of procedural success and safety. Under general anaesthesia, a small incision is made in the chest during the hybrid procedure, which uses Transesophageal Echocardiography (TEE) to localise the defect precisely. The occluder device is precisely positioned across the VSD by inserting a guide wire through the incision [23]. In a study by Wu L et al., the procedure was performed on 59 patients. All procedures were performed under the guidance of transesophageal echocardiography. The 57 procedures out of 59 (96.6%) were successful. With just one major complication (1.7%) and 14% minor complications, the success rate was 97%. Because of its low risk and successful procedure, hybrid transthoracic periventricular device closure for VSD is a good alternative strategy [24].

The success rate was 93.2% in a larger cohort of 250 patients, with improved left ventricular ejection fraction over time and few post-operative complications. Although 15% of patients experienced mild tricuspid regurgitation, most minor complications disappeared during follow-up. Because the hybrid approach reduces surgical trauma, recovery times are shortened and incisions are made smaller (2-4 cm) [25].

Hybrid interventions for other complex CHDs: The hybrid interventions are a combination of surgical and catheter-based techniques for the treatment of intricate CHD, especially in neonates, where single-modality treatment is risky. These aim to reduce Cardiopulmonary Bypass (CPB) time, minimise trauma, and optimise haemodynamic stability.

Intraoperative hybrid coarctation stenting in univentricular patients:

A study was done on 14 infants with aortic arch obstruction undergoing stenting during Glenn or Fontan procedures. The stent widened the transverse arch diameter from a mean of 5.1 mm to 9.8 mm. No re-coarctation was seen on follow-up, a durable, practical, CPB-free repair method that supports somatic growth was demonstrated by the peak Doppler velocity stabilising at 2.0 m/s [26].

Periventricular device closure of muscular and doubly-committed VSDs: Doubly-committed Subarterial VSDs:

Lin K et al. conducted a study between 2008 and 2010, in which 34 children were treated with Transoesophageal Echocardiography (TEE)-guided periventricular closure. There was a total success rate of 82% and 93% at discharge when increased to total closure, and 100% at 20 months. The procedure was safe and efficient; no significant complications were seen [27].

TECHNOLOGY-DRIVEN INNOVATIONS IN CHD SURGERY

3D Printing and Surgical Simulation in CHD

The 3D-printing is a new, transformative technology in managing surgical simulation of CHD. 3D-printing enhances intraoperative guidance, surgical training, and overall patient outcomes by creating patient-specific models [28]. A critical evaluation of the efficacy and accuracy of super-flexible 3D heart models fabricated through stereolithography printing was conducted by Shiraishi I et al., It was discovered that 3D-printed models enable advanced anatomical visualisation, which enhances comprehension of intricate cardiac structures. A study revealed that 68.4% of surgeons considered 3D models indispensable for decision-making, with a high accuracy rate of 0.54 mm in model replication [28].

Eleven residents used a 3D-printed surgical model to perform a surgical correction of aortic coarctation in a study by Cattapan C et al., These models have been experimentally shown to facilitate surgical simulations, allowing surgeons to practice procedures before actual operations, potentially improving surgical outcomes. Surgical residents' skills have improved significantly due to using 3D models for surgical simulation; after multiple simulations, their median performance increased from 65% to 83%. The difficulties caused by restricted access to operating rooms can be addressed by incorporating 3D-printing into surgical curricula to improve training opportunities [29].

Artificial Intelligence (AI) and Imaging-guided Planning

Artificial Intelligence (AI) has added new dimensions for the treatment of CHD through advanced image-guided planning. It enhances the accuracy of diagnosis by imaging techniques and machine learning algorithms, and personalises treatment planning, which facilitates tailored, timely interventions and improves overall patient outcomes [30-32].

The first large CT dataset was gathered from three separate CT machines in a study by Xu X et al., which included over 3750 CHD

patients over 14 years. The results of the trials reveal that it can attain a diagnosis accuracy of 86.03%, comparable to that of junior cardiovascular radiologists (86.27%) [30]. Pozza A et al., found that AI's ability to analyse large datasets improves risk stratification, allowing clinicians to identify high-risk patients earlier. Integrating genetic testing and imaging data allows for creating personalised treatment plans, which optimise care for diverse patient populations [31]. Despite its potential, challenges such as data privacy, bias, and the need for human oversight remain critical in implementing AI in clinical settings [32].

Intraoperative Navigation and Robotics

Intraoperative navigation and robotics have created many advancements in the surgical treatment of CHD with enhanced precision and reduced recovery times. The da Vinci system is successfully used in minimally invasive procedures, demonstrating safety and feasibility. Robotic Magnetic Navigation (RMN) is an effective tool for managing arrhythmias in CHD cases, especially when traditional methods don't work due to complex anatomical structures [33]. Yang Y et al., conducted a study on 160 patients undergoing CHD surgery. Using three 8 mm ports and one 15 mm port in the right chest, microscopic instruments were manipulated to complete defect closure or mitral valve plasty using the da Vinci S or Sensei (SI) robotic systems. It was successfully used in procedures such as atrial septal defect repair and mitral valve-plasty, with no conversion to open surgery, and no serious complications were reported [33]. A study by Khairy P et al., investigated the safety and efficacy of RMN-guided catheter ablation in patients with CHD. They discovered that it facilitates access to target heart chambers by surmounting obstacles such as distorted vascular pathways and complex post-surgical reconstructions. It enhances catheter manoeuvrability within the heart by employing soft and flexible catheters equipped with magnets, enabling robotic steering and orientation in 3D space [34]. A summary of recent advances in surgical techniques for CHD is shown in [Table/Fig-2] [16-22,24-29,33,34].

Authors of the study	Country	Year	Sample size	Procedure performed	Key post-operative outcomes	Conclusion
Liu Y et al., [16]	China	2006	23	Arterial switch operation for TGA/Taussig-Bing anomaly with pulmonary hypertension	Reduced pulmonary artery pressure; 20/23 survival	ASO safe in older infants with complex CHD
Xu Z et al., [17]	China	2004	61	Arterial switch operation for TGA and DORV with subpulmonary VSD	Cyanosis resolved; improved physical activity	ASO effective for complex TGA
Raju V et al., [18]	India	2024	390	Pulmonary valve-sparing repair for Tetralogy of Fallot	No mortality; low re-intervention	Excellent mid-term valve function
Martins RS et al., [19]	Multinational	2024	11,723	Valve-sparing vs transannular patch repair of TOF	Reduced mortality, ICU stay, ventilation time	VS superior to TAP
Moroi MK et al., [20]	USA	2025	139	Valve-sparing TOF repair with intra-operative balloon dilation	Less RV remodelling; low PR/PS	Suitable for small annulus TOF
Cassanello P [21]	Italy	2023	1	Hybrid Norwood palliation for HLHS	Successful staged palliation	Hybrid safe in selected HLHS
Cao JY et al., [22]	Multinational	2018	Meta-analysis	Hybrid vs conventional Norwood for HLHS	Higher early mortality in hybrid	Norwood preferred
Wu L et al., [24]	China	2023	59	Hybrid transthoracic, periventricular device closure of VSD	97% success; minimal complications	Safe, minimally invasive
Adilbekova A et al., [25]	Kazakhstan	2024	250	Hybrid periventricular VSD device closure	Improved LVEF; resolving TR	Good mid-term outcomes
Haas NA et al., [26]	Germany	2016	14	Hybrid intraoperative arch stenting in univentricular hearts	Stable arch diameter; no recoarctation	Durable CPB-free repair
Lin K et al., [27]	China	2013	34	Periventricular device closure of doubly-committed subarterial VSD	100% closure at 20 months	Safe and effective
Shiraishi I et al., [28]	Japan	2024	Multicentre	3D-printed cardiac models for surgical planning	High anatomical accuracy	Enhances pre-op planning

Cattapan C et al., [29]	Italy	2023	11	3D-printed surgical simulation training	Skill improvement (65% to 83%)	Improves surgical competency
Yang M et al., [33]	China	2012	160	Robotic ASD repair and mitral valve plasty	No open conversion; safe outcomes	Robotic surgery feasible
Khairy P et al., [34]	Canada	2024	Not specified	RMN-guided catheter ablation for CHD arrhythmias	Improved navigation and access	RMN effective in complex CHD

[Table/Fig-2]: Summary of recent advances in surgical techniques for congenital heart disease [16-22,24-29,33,34].

ASO: Arterial switch operation; TGA: Transposition of great arteries; DORV: Double outlet right ventricle; VSD: Ventricular septal defect; TOF: Tetralogy of Fallot; HLHS: Hypoplastic left heart syndrome; TAP: Transannular patch; PR: Pulmonary regurgitation; PS: Pulmonary stenosis; ICU: Intensive care unit; CPB: Cardiopulmonary bypass; LVEF: Left ventricular ejection fraction; RMN: Robotic magnetic navigation

Limitation(s)

The present narrative review has certain limitations. Formal systematic review methodology and quantitative meta-analysis were not performed. Several included studies were observational, single-centre, or based on small sample sizes, which may limit the generalisability of findings.

CONCLUSION(S)

The CHD management advancements are focused on long-term quality of life rather than survival. Patient stability and surgical preparedness are now carefully balanced with timely interventions, particularly in the neonatal period. Innovations such as valve-sparing repairs, hybrid procedures, and refined arterial switch operations have transformed outcomes for even the most complex lesions. At the same time, emerging technologies like 3D-printed heart models, AI-guided imaging, and robotic-assisted techniques enhance surgical precision and personalisation. Current advances indicate a progressive shift towards safer, more individualised, and technology-assisted care in CHD management, despite the persistence of challenges such as access, cost, and long-term data. Large multicentre prospective studies are required to evaluate long-term neurodevelopmental, functional, and quality-of-life outcomes following hybrid and technology-assisted congenital cardiac procedures.

REFERENCES

- Wu WM, He JX, Shao XB. Incidence and mortality trend of congenital heart disease at the global, regional, and national level, 1990-2017. *Medicine (Baltimore)*. 2020;99(23):e20593. Doi: 10.1097/MD.00000000000020593.
- Bouma BJ, Mulder BJ. Changing landscape of congenital heart disease. *Circ Res*. 2017;120(6):908-22. Doi: 10.1161/CIRCRESAHA.116.309302.
- Yasuhara J, Garg V. Genetics of congenital heart disease: A narrative review of recent advances and clinical implications. *Transl Pediatr*. 2021;10(9):2366-86. Doi: 10.21037/tp-21-297.
- van der Bom T, Zomer AC, Zwinderman AH, Meijboom FJ, Bouma BJ, Mulder BJ. The changing epidemiology of congenital heart disease. *Nat Rev Cardiol*. 2011;8(1):50-60. Doi: 10.1038/nrcardio.2010.166.
- Fazekas-Pongor V, Csáky-Szunyogh M, Fekete M, Mészáros Á, Cseh K, Péntzes M. Congenital heart diseases and parental occupational exposure in a Hungarian case-control study in 1997 to 2002. *Congenital Anom (Kyoto)*. 2021;61(2):55-62. Doi: 10.1111/cga.12401.
- Wood MK. Acyanotic lesions with increased pulmonary blood flow. *Neonatal Netw*. 1997;16(3):17-25; quiz 26-28. PMID:9155358.
- Rao PS. Management of congenital heart disease: State of the art-part II-cyanotic heart defects. *Children (Basel)*. 2019;6(4):54. Doi: 10.3390/children6040054.
- Ossa Galvis MM, Bhakta RT, Tarmahomed A, Mendez MD. Cyanotic heart disease. In: *StatPearls [Internet]*. Treasure Island (FL): StatPearls Publishing; 2025 Jan-. Updated 2023 Jun 26. PMID:29763177.
- Shrivastava S. Timing of surgery/catheter intervention in common congenital cardiac defects. *Indian J Pediatr*. 2000;67(3 Suppl):S2-6. Retraction in: *Indian J Pediatr*. 2021;88(11):1165. Corrected and republished in: *Indian J Pediatr*. 2000;67(4):273-77. Doi: 10.1007/BF02758170.
- Faateh M, Hogue S, Mehdizadeh-Shrifi A, Kulshrestha K, Hossain MM, Lehenbauer DG, et al. Is timing as critical for repair of dextro-transposition of the great arteries with ventricular septal defect without outflow tract obstruction? *JTCVS Open*. 2024;24:350-58. Doi: 10.1016/j.jxon.2024.10.015.
- Damkjær M, Garne E, Loane M, Urhoj SK, Ballardini E, Cavero-Carbonell C, et al. Timing of cardiac surgical interventions and post-operative mortality in children with severe congenital heart defects across Europe: Data from the EUROlinkCAT study. *J Am Heart Assoc*. 2023;12(24):e029871. Doi: 10.1161/JAHA.122.029871.
- Masaki S, Ando Y, Nakano T. Surgical management of Norwood procedure for atypical aortic arch. *World J Pediatr Congenit Heart Surg*. 2024;15(5):581-87. Doi: 10.1177/21501351241235953.
- Rychik J, Goldberg D, Rand E, Semeao E, Russo P, Dori Y, et al. End-organ consequences of the Fontan operation: Liver fibrosis, protein-losing enteropathy and plastic bronchitis. *Cardiol Young*. 2013;23(6):831-40. Doi: 10.1017/S1047951113001650.
- Sharma VJ, Iyengar AJ, Zannino D, Gentles T, Justo R, Celermajer DS, et al. Protein-losing enteropathy and plastic bronchitis after the Fontan procedure. *J Thorac Cardiovasc Surg*. 2021;161(6):2158-64.e4. Doi: 10.1016/j.jtcvs.2020.07.107.
- Smith AH, Shin AY, Tabbutt S, Banerjee M, Zhang W, Borasino S, et al. Age at surgery and outcomes following neonatal cardiac surgery: An analysis from the Pediatric Cardiac Critical Care Consortium. *J Thorac Cardiovasc Surg*. 2023;165(4):1528-35.e7. Doi: 10.1016/j.jtcvs.2022.05.029.
- Liu Y, Hu S, Shen X, Li S, Wang X, Yan J, Cui B. Indications of arterial switch operation for complex congenital heart defect with severe pulmonary hypertension and ventriculoarterial discordant connection. *Natl Med J China*. 2006;86:08-13. Doi: 10.3760/j.issn:0376-2491.2006.01.008.
- Xu Z, Ding W, Su Z, Chen L, Shi Z, Zhu D. Arterial switch operation for transposition of the great arteries and double outlet of right ventricle with subpulmonary ventricular septum defect. *Chin J Thorac Cardiovasc Surg*. 2004;20:455-58. Doi: 10.3760/j.issn:0529-5815.2004.08.002.
- Raju V, Srinivasan N, Kadavanoor D, Moorthy R, Jothinath K, Gangadharan S, et al. Mid-term results of pulmonary valve-sparing repair for Tetralogy of Fallot with pulmonary stenosis. *World J Pediatr Congenit Heart Surg*. 2024;21501351241279519. Doi: 10.1177/21501351241279519.
- Martins RS, Fatimi AS, Mahmud O, Qureshi S, Nasim MT, Virani SS, et al. Comparing clinical and echocardiographic outcomes following valve-sparing versus transannular patch repair of Tetralogy of Fallot: A systematic review and meta-analysis. *Interdiscip Cardiovasc Thorac Surg*. 2024;39(1):vae124. Doi: 10.1093/icvts/vae124.
- Moroi MK, Feng I, Vinogradsky AV, Yang CG, Nguyen SN, Kalfa DM, et al. Mid-term outcomes of valve-sparing repair with intraoperative balloon dilation in Tetralogy of Fallot. *World J Pediatr Congenit Heart Surg*. 2025 May 29;21501351251321528. Doi: 10.1177/21501351251321528.
- Cassanello P. Converting an infant with borderline left heart structures to biventricular circulation after an initial hybrid Norwood approach: A case report. *Eur Heart J Case Rep*. 2023;7(4). Doi: 10.1093/ehjcr/ytad133.
- Cao JY, Lee SY, Phan K, Ayer J, Celermajer DS, Winlaw DS. Early outcomes of hypoplastic left heart syndrome infants: Meta-analysis of studies comparing the hybrid and Norwood procedures. *World J Pediatr Congenit Heart Surg*. 2018;9(2):224-33. Doi: 10.1177/2150135117752896.
- Tsai S, Wang J, Chen S. Hybrid procedure for congenital heart diseases (CHDs). In: *Congenital Heart Disease*. Singapore: Springer; 2023. p.231-37. Doi: 10.1007/978-981-99-6582-3_11.
- Wu L, Öztürk E, Ye D, Zhang X, Li B, Zhu D, et al. Hybrid transthoracic periventricular device closure of ventricular septal defects: Single-center experience. *Figshare*. 2023. Doi: 10.6084/m9.figshare.22132328.
- Adilbekova A, Nurkeev B, Marassulov S, Kozhakhmetov S. Mid-term outcome of the hybrid method of ventricular septal defect closure in children. *J Clin Med Kaz*. 2024;21(2):44-50. Doi: 10.23950/jcmk/14401.
- Haas NA, Happel CM, Blanz U, Lasser KT, Kantzis M, Kececioglu D, Sandica E. Intraoperative hybrid stenting of recurrent coarctation and arch hypoplasia with large stents in patients with univentricular hearts. *Int J Cardiol*. 2016;204:156-63. Doi: 10.1016/j.ijcard.2015.11.136.
- Lin K, Zhu D, Tao K, Gan C, Tang H, Feng Y, An Q. Hybrid periventricular device closure of doubly committed subarterial ventricular septal defects: Mid-term results. *Catheter Cardiovasc Interv*. 2013;82(3):E225-32. Doi: 10.1002/ccd.24869.
- Shiraishi I, Yamagishi M, Hoashi T, Kato Y, Iwai S, Ichikawa H, et al. Evaluation of the efficacy and accuracy of super-flexible three-dimensional heart models of congenital heart disease made via stereolithography printing and vacuum casting: A multicenter clinical trial. *J Cardiovasc Dev Dis*. 2024;11(12):387. Doi: 10.3390/jcdd11120387.
- Cattapan C, Guariento A, Bertelli F, Galliotto F, Vazzoler C, Magagna P, et al. The introduction of surgical simulation on three-dimensional-printed models in the cardiac surgery curriculum: An experimental project. *J Cardiovasc Med (Hagerstown)*. 2023;25:165-72. Doi: 10.2459/jcm.0000000000001577.
- Xu X, Jia Q, Yuan H, Qiu H, Dong Y, Xie W, et al. A clinically applicable AI system for diagnosis of congenital heart diseases based on computed tomography images. *Med Image Anal*. 2023;102953. Doi: 10.1016/j.media.2023.102953.
- Pozza A, Zanella L, Castaldi B, Di Salvo G. How will artificial intelligence shape the future of decision-making in congenital heart disease? *J Clin Med*. 2024;13:102996. Doi: 10.3390/jcm13102996.
- Mohsin S, Gapizov A, Ekhatov C, Ain NU, Ahmad S, Khan M, et al. The role of artificial intelligence in prediction, risk stratification, and personalised treatment planning for congenital heart diseases. *Cureus*. 2023;15(8):e44374. Doi: 10.7759/cureus.44374.

[33] Yang M, Gao C, Xiao C, Wang G, Wang J, Wu Y. Clinical experiences on correction of congenital heart diseases with robotic technology: A report of 160 cases. *Natl Med J China*. 2012;92(32):2261-64. Doi: 10.3760/CMA.J.ISSN.0376-2491.2012.32.009.

[34] Khairy P, Dyrda K, Mondésert B, Aguilar M, Dubuc M, Cadrin-Tourigny J, et al. Overcoming access challenges to treat arrhythmias in patients with congenital heart disease using robotic magnetic-guided catheter ablation. *J Clin Med*. 2024;13(18):5432. Doi: 10.3390/jcm13185432.

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