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Tiny Hearts, Big Surgeries: Pediatric Cardiac Interventions for Congenital Heart Defects

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Abstract

Congenital heart defects (CHDs) are the most common birth anomalies, affecting millions of infants worldwide. Despite advancements in diagnostic and therapeutic techniques, CHDs remain a major cause of childhood morbidity and mortality. This review aims to provide a comprehensive analysis of the current understanding of CHDs, covering their etiology, diagnosis, treatment, and future directions. The review examines the impact of prenatal screening techniques, such as fetal echocardiography and non-invasive genetic testing, in enabling early diagnosis. Surgical and catheter-based interventions are discussed, alongside their effectiveness in improving survival rates and reducing complications. Additionally, the review addresses the long-term challenges faced by CHD patients, including neurodevelopmental issues and the need for lifelong care. Furthermore, the review underscores the importance of multidisciplinary care and standardized guidelines for improved patient outcomes. Looking ahead, this review emphasizes the need for precision medicine approaches to tailor treatment strategies based on individual genetic profiles. Future research should focus on advancing minimally invasive procedures and refining prenatal diagnostic tools. Increased global collaboration and data-sharing initiatives will be essential for driving innovation and enhancing the quality of life for individuals with CHDs.

Keywords: Clinical studies, Congenital heart defects, Diagnosis, Genetic factors, Minimally invasive procedures, Prenatal screening, Treatment strategies

Introduction

CHDs are among the most prevalent birth defects (Table 1), affecting approximately 1% of live births globally [1-3]. CHDs are structural abnormalities of the heart or great vessels that are present at birth. They are among the most common birth defects, affecting approximately 1% of live births globally, which translates to about 40,000 births per year in the United States alone [4]. The prevalence of CHDs varies significantly across different populations and regions, influenced by factors such as genetics, maternal health, and environmental exposures [5-7].

The global incidence of CHDs is estimated to be around 8 - 9 per 1,000 live births, with variations depending on the diagnostic criteria and population studied [8]. In some regions, such as Eastern China, the average incidence has been reported as high as 16.0 per 1,000 births, reflecting a 62.2% increase from 2014 - 2018 [9]. In contrast, a study in Jordan found an incidence of 17.8 per 1,000 live births, which increased to 24.6 per 1,000 when including patent ductus arteriosus (PDA) in preterm infants [8]. In East Africa, a systematic review indicated that ventricular septal defects (VSD) and atrial septal defects (ASD) accounted for a significant proportion of CHDs, with a pooled prevalence of 29.92% for VSD and 10.36% for ASD [10]. These findings highlight the need for improved screening and early detection strategies in various regions to address the high prevalence of these defects.

Several risk factors have been identified in association with CHDs. Maternal obesity has been linked to an increased risk of CHDs, with studies indicating a dose-response relationship between maternal body mass index and the likelihood of defects in offspring [11]. Additionally, maternal diabetes, particularly pregestational diabetes, has been shown to significantly elevate the risk of CHDs compared to non-diabetic pregnancies [12]. Other factors include advanced maternal age, exposure to teratogens, and genetic predispositions. For instance, a study found that women aged ≤20 years or ≥35 years had a higher risk of having babies with CHDs [12]. Furthermore, the presence of congenital urological anomalies has been associated with an increased likelihood of concurrent CHDs, particularly in complex cases [13].

The prognosis for individuals with CHDs has improved significantly due to advancements in medical and surgical interventions. However, adults with CHDs face ongoing health challenges, including an increased risk of coronary artery disease and cognitive impairments [14, 15]. The

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Table 1: Etiology of CHDs.

Factor	Description	Examples	Pathophysiology	Clinical implications
Genetic factors	Mutations or chromosomal abnormalities	Trisomy 21, 22q11.2 deletion	Disrupted cardiac development pathways	Increased risk of septal defects, valve abnormalities
Single-gene mutations	Defects caused by mutations in a single gene	NKX2-5, GATA4, TBX5 mutations	Faulty transcription factor regulation	Conotruncal defects, ASD
Polygenic factors	Multiple gene interactions	CHD with complex inheritance patterns	Combined gene effects on heart formation	Increased variability in clinical presentation
Environmental factors	External influences during pregnancy	Maternal diabetes, rubella, alcohol exposure	Teratogenic effects on embryonic heart tissue	Higher prevalence of conotruncal abnormalities
Maternal health	Pre-existing conditions	Obesity, hypertension	Impaired placental circulation	Increased fetal hypoxia and CHD risk
Epigenetic factors	Gene expression changes without DNA alteration	DNA methylation, histone modification	Altered gene regulation	May influence CHD severity and progression
Teratogenic agents	Substances causing fetal malformations	Certain medications, toxins	Direct interference with heart morphogenesis	Structural anomalies, growth restrictions
Multifactorial causes	Interaction of genetic and environmental factors	Maternal illness + genetic predisposition	Combined pathophysiological effects	Complex CHD presentations with variable severity

long-term management of these patients requires a shift in focus from immediate surgical outcomes to the prevention of cardiovascular morbidity and the promotion of overall health and quality of life. Research indicates that adults with CHDs often experience executive function deficits, which can impact their academic and professional achievements [15]. This underscores the importance of comprehensive care that addresses both the physical and cognitive aspects of living with CHDs.

Advances in pediatric cardiac surgery have significantly improved survival rates, allowing many children with CHDs to reach adulthood [16, 17]. However, these patients often face a range of long-term complications and comorbidities that necessitate ongoing medical care and intervention [18]. This review explores various pediatric cardiac interventions for CHDs, their outcomes, and the challenges faced in managing these complex conditions.

Types of CHDs

CHDs can be classified into two main categories: acyanotic and cyanotic defects [19, 20]. Acyanotic defects, such as VSD and ASD, typically allow for normal oxygenation of blood, while cyanotic defects, such as tetralogy of Fallot, result in reduced oxygen levels in the bloodstream [21, 22]. The choice of intervention often depends on the type and severity of the defect, as well as the patient's overall health status [23, 24].

Acyanotic heart defects include: (i) VSD: This is the most common CHDs, characterized by a hole in the wall separating the two ventricles. It can lead to increased blood flow to the lungs and heart failure if not treated [25]. (ii) ASD: An ASD is a hole in the wall between the two atria, which can lead to heart enlargement and pulmonary hypertension over time [26]. (iii) PDA: This defect occurs when the ductus arteriosus, a blood vessel that should close after birth, remains open, leading to increased blood flow to the lungs [27, 28]. (iv) Coarctation of the aorta: This condition involves a narrowing of the aorta, which can lead to high blood pressure and heart failure if not addressed [29, 30].

ASDs are characterized by a hole in the interatrial septum, which separates the left and right atria. The three major types of ASD are ostium secundum, ostium primum, and sinus venosus defects. Unrepaired ASDs can lead to right heart volume overload, atrial arrhythmias, and pulmonary arterial hypertension [31]. Approximately 6 - 10% of all CHDs are ASDs, with a female-to-male predominance of 2:1 [32]. VSDs involve a hole in the ventricular septum, allowing blood to flow between the left and right ventricles. VSDs are the most common type of CHDs, accounting for about 51% of cases [10]. They can vary in size and may lead to significant hemodynamic consequences if not treated. Complex CHDs include conditions such as tetralogy of Fallot, transposition of the great arteries, and hypoplastic left heart syndrome [33, 34]. These defects often require surgical intervention and can lead to severe complications if not addressed early.

Cyanotic heart defects include conditions such as: (i) Tetralogy of fallot: This defect consists of four heart abnormalities that result in insufficient oxygenated blood reaching the body. It is one of the most common cyanotic defects, accounting for about 7% of all CHDs [35]. (ii) Transposition of the great arteries: In this condition, the two main arteries leaving the heart are reversed, leading to a separation of oxygen-rich and oxygen-poor blood. This defect requires immediate medical intervention after birth [36]. (iii) Tricuspid atresia: This defect occurs when the tricuspid valve is absent or malformed, preventing blood from flowing from the right atrium to the right ventricle [37, 38]. (iv) Total anomalous pulmonary venous return: In this condition, the pulmonary veins do not connect normally to the left atrium, leading to oxygen-poor blood circulated throughout the body [39, 40].

Interventional Techniques

Pediatric cardiac interventions for CHDs have evolved significantly, offering less invasive alternatives to traditional surgical methods [41]. These interventions are crucial for managing the high prevalence of CHDs in children, providing effective treatment options that improve outcomes and quality of life [42]. The development and application of innovative devices and techniques have been pivotal in advancing pediatric cardiology. Interventions for CHDs can be broadly categorized into surgical and non-surgical approaches. Surgical interventions may include open-heart surgery to repair structural defects, while non-surgical methods often involve catheter-based techniques to close defects or dilate narrowed vessels [43, 44]. This section will explore the various aspects of pediatric cardiac interventions, including innovations, procedural outcomes, and the role of imaging in treatment planning.

Surgical interventions

Surgical repair remains the cornerstone of treatment for many CHDs. For instance, the closure of VSDs and ASDs is commonly performed to prevent heart failure and pulmonary hypertension [45]. The Fontan procedure is a specialized surgical intervention for patients with single ventricle physiology, aiming to improve hemodynamics and reduce symptoms [46]. Studies have shown that surgical interventions can lead to significant improvements in growth and nutritional status in malnourished children with CHDs [47]. Despite the rise of less invasive techniques, traditional surgery remains crucial for certain cases due to its comprehensive approach to correcting structural heart anomalies.

Open-heart surgery involves a full mid-line sternotomy, which has been the gold standard for over 50 years. It allows surgeons to directly access the heart and perform necessary repairs or corrections [48]. Cardiopulmonary bypass is essential for open-heart surgeries; cardiopulmonary bypass supports circulation and oxygenation during the procedure. Pediatric cardiopulmonary bypass is complex due to the unique physiological and anatomical considerations in children, requiring specialized equipment and techniques to minimize hemodilution and manage temperature variations [49]. Children who undergo traditional surgeries may face late complications such as heart failure and arrhythmias, which can impact their long-term health and quality of life [50].

Non-surgical interventions

Non-surgical interventions, such as transcatheter closure of ASDs and VSDs, have gained popularity due to their minimally invasive nature. These procedures can often be performed under sedation, reducing recovery time and hospital stays [51]. Recent studies have demonstrated the efficacy of high-flow nasal cannula oxygen therapy during procedural sedation, improving oxygen saturation levels in pediatric patients with CHDs [52]. Techniques such as ministernotomy and thoracotomy have been developed to reduce the invasiveness of traditional surgeries. These approaches offer benefits like reduced recovery times and improved cosmetic outcomes, without compromising the effectiveness of the surgical correction [48, 53].

Studies indicate that minimally invasive surgeries can significantly improve the quality of life for pediatric patients, particularly in terms of physical appearance and recovery experience [54]. The research included 459 children aged 2 to 18 years with CHD, treated at Second Xiangya Hospital from July 2016 to June 2017. Among these, 219 underwent minimally invasive surgery, while 240 had traditional surgery. The quality of life was evaluated based on reports from the parents of the children. The study aimed to determine how different surgical methods impacted various dimensions of quality of life. A significant finding was that children who underwent minimally invasive surgery reported higher scores related to perceived physical appearance compared to those who had traditional surgery. This difference was statistically significant ($p = 0.004$). The type of surgery (minimally invasive vs traditional) was identified as an independent influencing factor specifically for issues related to perceived physical appearance in children with CHD. For other aspects of quality of life, such as problems related to cardiac symptoms, drug treatment, anxiety regarding treatment, cognitive psychology, and communication, there were no significant differences between the two surgical groups. This suggests that the surgical approach did not independently influence these dimensions. The study concluded that minimally invasive surgery significantly improves the perception of physical appearance in children with CHD, thereby enhancing their overall quality of life compared to traditional surgical methods. These results highlight the importance of surgical technique in the postoperative quality of life for children with CHD, particularly concerning their self-image and physical appearance [54].

Role of imaging in treatment planning

CHDs are a diverse group of defects that are common worldwide, necessitating effective imaging techniques for management and treatment planning (Figure 1) [55]. Table 2 presents various techniques used to diagnose CHDs. Cardiovascular magnetic resonance imaging (CMRI) is

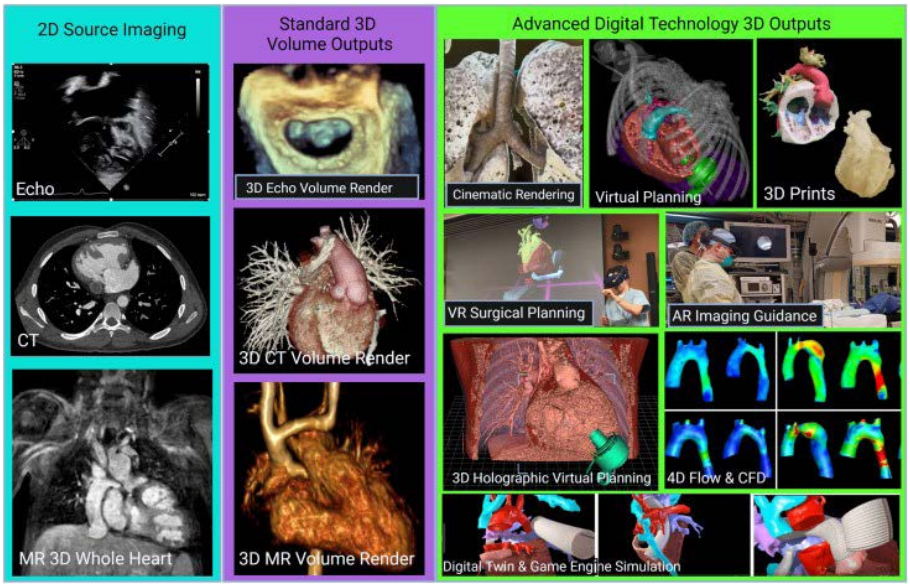

Figure 1: Advanced digital technology 3D outputs in CHD imaging [55].

Table 2: Diagnostic techniques for CHDs.

Technique	Description	Application	Advantages	Limitations
Fetal echocardiography	Ultrasound imaging of the fetal heart	Early prenatal diagnosis	Non-invasive, real-time imaging	Operator-dependent, limited resolution
CMRI and chest tomography	Advanced imaging techniques	Detailed anatomical assessment	High-resolution, 3D visualization	Requires sedation in children
Pulse oximetry screening	Measures oxygen levels in newborns	Early postnatal screening	Non-invasive, quick	May miss some complex CHDs
Genetic testing	Analyzes genetic mutations or chromosomal anomalies	Identifying hereditary CHDs	Detects underlying causes	Expensive, may not cover all mutations
Electrocardiogram	Measures the heart's electrical activity	Detects arrhythmia, conduction issues	Readily available, low-cost	Limited anatomical detail
Chest X-ray	Imaging to assess heart size and shape	Detects heart enlargement or fluid buildup	Quick, accessible	Limited sensitivity for mild defects
Cardiac catheterization	Invasive procedure to measure heart pressures	Diagnoses complex defects	Direct hemodynamic assessment	Invasive, risk of complications
3D printing and modeling	Patient-specific anatomical models	Pre-surgical planning	Improved surgical precision	High cost, not widely available

highlighted as a crucial non-invasive imaging modality that avoids ionizing radiation, making it particularly suitable for children. This is essential for guiding medical and surgical interventions, monitoring disease progression, and identifying complications. A study by Moscatelli et al. [56] emphasized that CMRI provides detailed images of cardiac anatomy and function. It utilizes two-dimensional and three-dimensional steady-state free precession techniques to accurately assess heart structures, volumes, and overall function, which is vital for surgical planning. CMRI is capable of characterizing myocardial tissue, allowing for the identification of conditions such as fat deposition, fibrosis, or edema. This capability enhances the understanding of the myocardial environment in CHD patients. The use of contrast agents in CMRI can provide valuable information about vascular and valvular blood flow, as well as overall cardiovascular hemodynamics. This is crucial for evaluating the effectiveness of treatments. CMRI can identify coronary artery abnormalities, serving as a non-invasive alternative to traditional invasive angiography and cardiovascular computed tomography. Despite its advantages, the review notes that CMRI has limitations, including the need for specialized expertise in CHDs, potential contraindications in patients with certain devices, longer acquisition times, and the requirement for breath-holding, which may necessitate anesthesia in younger children. In summary, the review underscored the pivotal role of CMRI in the management of CHDs in pediatric patients, while also addressing its limitations and the need for specialized knowledge in its application [56].

Innovations in pediatric cardiac interventions

Indian pediatric cardiologists have made significant contributions to the field by developing cost-effective and innovative solutions such as the MyVal transcatheter heart valve and the Konar-MF occluder. These devices have been instrumental in addressing complex clinical problems associated with CHDs [57]. The study notes that Indian centers have published some of the largest series on specific procedures, such as: (i) Transcatheter closure of sinus venosus ASD: A technique for closing a specific type of heart defect and (ii) Ruptured sinus of valsalva aneurysm: Addressing a rare but serious condition affecting the heart. The collaboration between pediatric and adult cardiologists has led to the adaptation of techniques and hardware from adult coronary interventions, enhancing the treatment options available for pediatric patients. These results illustrate the significant advancements and contributions made by Indian pediatric cardiologists in addressing the challenges of CHDs, showcasing their innovative spirit and commitment to improving pediatric cardiac care. The use of indigenous devices and techniques, such as static balloon dilatation of the interatrial septum and balloon-assisted ASD device implantation, has been widely adopted globally [57].

Transcatheter interventions have been shown to be feasible and effective, even in challenging cases like hypoplastic left heart syndrome and tetralogy of Fallot, providing a viable alternative to surgical repair [58].

Outcomes of Pediatric Cardiac Interventions

The outcomes of pediatric cardiac interventions vary based on several factors, including the type of defect, timing of intervention, and presence of comorbidities. For example, children with complex CHDs who undergo early surgical intervention tend to have better long-term outcomes compared to those who receive delayed treatment [59]. A study from Malaysia reported an overall survival rate of 88% at one year for children with CHDs, highlighting the importance of timely surgical intervention [59].

Postoperative cardiac catheterizations are crucial for addressing both anatomical and hemodynamic issues in high-risk patients, guiding subsequent treatments with satisfactory outcomes. These procedures have a high success rate and are often necessary for confirming diagnoses and planning further interventions [60]. The study evaluated the indications and outcomes of postoperative cardiac catheterizations in children following congenital heart surgeries. The study reviewed 192 patients with a median age of 2.3 months and a median weight of 4.2 kg. The catheterizations were performed on a median postoperative day of 7 (IQR 2 to 17 days) after surgery. A significant majority of the patients had complex heart defects, with 79.9% classified as having great complexity. Additionally, 46.4% had a high disease severity index, and 75% had a high Aristotle level of surgical complexity. The catheterizations confirmed 66% of suspected diagnoses. Notably, hemodynamical anomalies were confirmed more frequently than anatomical lesions (81.3% vs 53.7%, $p < 0.001$). Among confirmed anatomical lesions, residual issues were more common than new lesions created by surgery (88.5% vs 40.4%, $p < 0.001$). The study found that new diagnoses were identified in 36.5% of the patients, indicating that catheterizations can reveal previously undetected issues. Findings from the catheterizations led to catheter-based or surgical interventions in 120 patients, which is 62.5% of the total. The success rate for transcatheter interventions was high at 97.7%, with 89.5% being immediate and 27.8%

performed across fresh suture lines. Some patients require repeated catheterization, with 76% of these being interventional. This was necessary for 25 patients, accounting for 13% of the total. The study identified significant risk factors for 12-month mortality, including a high index of disease severity (overall response (OR): 16.26, 95% confidence interval (CI): 3.72 to 71.17), ECMO support (OR: 10.35, 95% CI: 2.78 to 38.56), delayed sternal closure (OR: 4.66, 95% CI: 1.25 to 17.32), and surgically-acquired lesions (OR: 3.70, 95% CI: 1.22 to 11.16). In conclusion, postoperative cardiac catheterizations in high-risk pediatric patients provide critical insights into both anatomical and hemodynamic issues, guiding subsequent treatment with favorable outcomes [60].

Percutaneous catheter interventions for congenital perimembranous VSDs have a high success rate of 98.2%, although they carry a risk of cardiac conduction system complications, such as heart block [61]. The study included a total of 1650 pediatric patients from 8 different publications. The average age of these children ranged from 3.44 to 8.67 years old. The success rate of the percutaneous catheter intervention for treating perimembranous VSDs was reported to be 98.2% (95% CI: 97.1 to 99.4%, I2 = 69.4%; $p < 0.001$). This means that nearly all patients had successful implantation of the device used for the procedure. However, there were some complications related to the cardiac conduction system. The overall incidence of these complications was 17.4% (95% CI: 8.4 to 26.4%, I2 = 96.1%; $p < 0.001$). This indicates that a significant number of patients experienced issues with their heart's electrical system after the procedure. Among these complications, the most common was heart block, which occurred in 14.8% (95% CI: 6.4 to 23.3%, I2 = 96.9%; $p = 0.001$) of the patients. Heart block can affect how well the heart beats and can lead to serious issues if not monitored. The study also found that impulse formation disorders occurred in 4.1% (95% CI: 0.7 to 7.6%, I2 = 91.7%; $p = 0.019$) of the patients, while the incidence of complete atrioventricular block (cAVB) was relatively low at 0.8% (95% CI: 0.3 to 13%, I2 = 0.0%; $p = 0.001$). cAVB is a serious condition that requires immediate medical attention. The researchers identified risk factors for developing new arrhythmia (irregular heartbeats) after the intervention. These included the size of the VSD, and the size of the device used for closure. Specifically, larger sizes of both the VSD and the device were associated with a higher risk of arrhythmias. Overall, the findings suggest that while the percutaneous catheter intervention is generally safe and effective, there are notable risks, particularly concerning the heart's conduction system, which needs to be carefully managed [61].

Simultaneous transthoracic interventions for multiple cardiac defects have been shown to be feasible and safe, with good short-term outcomes and no serious complications reported [62]. The study involved 20 pediatric patients with multiple CHDs who underwent simultaneous transthoracic interventions. All patients were successfully treated without needing to convert to thoracotomy, which is a more invasive surgical approach. The average age of the patients was approximately 18.8 months, with a range from 4 to 36 months. The group included 15 males and 5 females, with an average weight of 8.3 kg. The types of defects treated included: ASD and perimembranous VSD in 7 patients, PDA and ASD in 6 patients, perimembranous VSD and PDA in 2 patients, perimembranous VSD and valvular pulmonary stenosis in 2 patients, ASD and pulmonary stenosis in 2 patients, and doubly committed subarterial VSD and pulmonary stenosis in 1 patient. The procedures (Figure 2) were performed

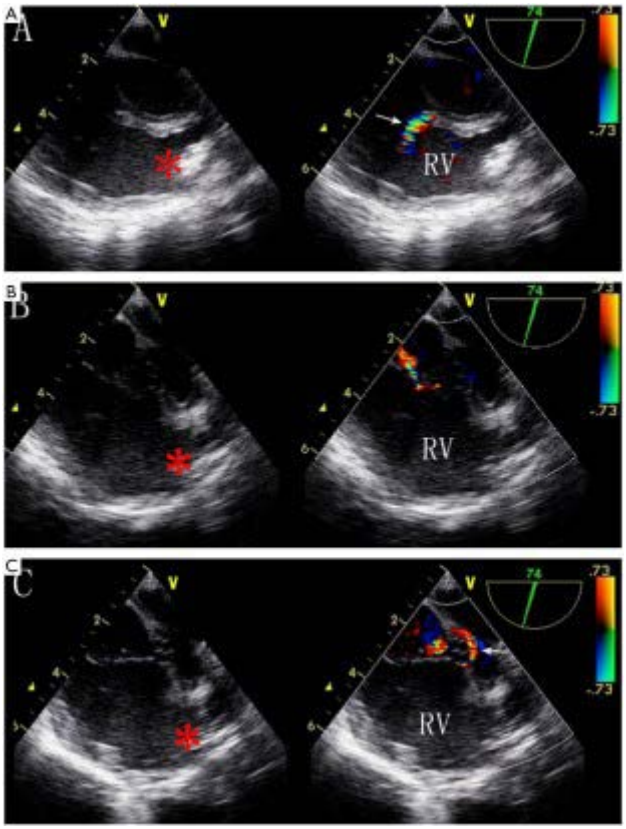

Figure 2: Transesophageal echocardiography shows the procedure of perimembranous VSD and valvular pulmonary stenosis [62].

under general anesthesia, and the average operation time was about 75 min, ranging from 56 to 120 min. The incisions made were typically small, measuring 1.5 to 2.0 cm. During the follow-up period, which lasted from 5 to 56 months (average of 25.2 months), all patients showed good growth and development. There were no serious complications reported, such as deaths, cAVB, or infections. The study highlighted that the time spent under anesthesia, and the length of hospital stay were significantly shorter for the intervention group compared to those who underwent traditional surgery with cardiopulmonary bypass. Overall, the results suggest that simultaneous transthoracic intervention for multiple cardiac defects in children is a feasible and safe procedure, yielding positive short-term outcomes [62].

A study by Philip et al. [63] focused on the feasibility and safety of percutaneous cardiac interventions (PCI) in infants weighing ≤1000 g, particularly those with CHDs or acquired heart defects. A retrospective review was conducted, analyzing 148 consecutive PCIs performed on infants weighing ≤1000 g from June 2015 to May 2021. This design allowed for a comprehensive assessment of the interventions over a significant period. The study reported a remarkable procedural success rate of 100% for all PCIs performed. This indicated that every procedure was completed without failure, showcasing the effectiveness of the interventions used in this vulnerable population. For the transcatheter closure of PDA, the major adverse event rate was 3%. This suggests that while there are risks involved, they are relatively low for this specific procedure. Notably, there were no major adverse events reported for other types of PCI performed on these infants. This highlights the safety of the interventions beyond transcatheter closure of PDA. The findings supported the conclusion that it was feasible to perform PCIs in infants weighing ≤1000 g with CHD and acquired heart defects using currently available technologies. The low rate of major adverse events further emphasizes the safety of these procedures in such a delicate patient population. In summary, the study demonstrated that PCI can be safely and effectively performed in very low birth weight infants, providing a promising option for managing CHDs and acquired heart defects in this high-risk group [63].

The EUROlinkCAT study highlights that while the overall prognosis for most CHDs is good, certain defects still carry significant postoperative mortality risks [64]. The study aimed to evaluate the timing of cardiac surgeries, the number of surgeries performed, and the 30-day postoperative mortality rates for children with severe CHDs across Europe. The median age for the first surgical intervention for children with severe CHDs was found to be 3.6 weeks (95% CI: 2.6 to 4.5 weeks). The timing of the first surgery was consistent across the nine European regions studied, indicating a standardized approach to surgical intervention for most subtypes of severe CHD. Children with hypoplastic left heart syndrome underwent the highest number of cardiac surgeries, with a median of 4.4 surgeries (95% CI: 3.1 to 5.6) within the first five years of life. The 30-day postoperative mortality rate varied significantly among different types of severe CHD. For instance: (i) Tetralogy of Fallot had a mortality rate of 1.1% (95% CI: 0.5% to 2.1%) and (ii) Ebstein anomaly had a much higher mortality rate of 23% (95% CI: 12% to 37%). The study highlighted that the highest mortality rates were observed in children undergoing surgery within the first month of life. The overall five-year survival rate for children with severe CHDs was reported to be less than 90% for most types of CHDs. However, exceptions included transposition of the great arteries, tetralogy of Fallot, and coarctation of the aorta, which had better survival outcomes. The study concluded that there were no major differences in the timing of surgeries, postoperative mortality rates, and the number of operations performed across the nine regions in Europe. These results provide valuable insights into the management and outcomes of surgical interventions for children with severe CHDs, emphasizing the need for continued monitoring and improvement in surgical practices [64].

Clinical Studies

Pediatric cardiac interventions for CHD have evolved significantly, with various studies highlighting the effectiveness and safety of different approaches. These interventions range from traditional surgical methods to minimally invasive and transcatheter techniques, each offering distinct benefits and outcomes. The choice of intervention often depends on the specific type of defect, the patient's condition, and the available resources. This section provides a detailed overview of clinical studies and outcomes associated with these interventions.

Transcatheter interventions are increasingly favored for managing residual shunt lesions post-surgery due to their minimally invasive nature, high safety profile, and reduced recovery times. A study by Chowdhury et al. [65] involving patients with residual lesions after congenital cardiac surgery showed that transcatheter closure effectively managed these defects without significant complications, such as vascular access issues or procedure-related mortality. The study included seven patients with postoperative residual shunt lesions. Among them, four were male and three were female, with a median age of 11 years, ranging from 1 to 28 years. Out of the seven patients, six (85.7%) underwent elective closures of their residual lesions, while one patient (14.3%) required an emergency intervention. This indicates a preference for planned procedures when possible. The average time between the initial surgery and the subsequent transcatheter intervention was 6.6 years, with a range from as short as 15 days to as long as 13 years. This highlights the variability in the timing of interventions based on individual patient circumstances. The average hospital stay for all patients was 7 days, with a range of 4 to 22 days. This suggests that the transcatheter approach may allow for relatively short recovery times compared to traditional surgical methods. The average follow-up period for the patients was 5.84 years, indicating a long-term assessment of the outcomes following the interventions. Importantly, there were no reported complications related to vascular access, such as postprocedural heart block, hemolysis, significant new valvular regurgitation, or procedure-related mortality. This emphasized the safety profile of transcatheter interventions in this patient population. The study concluded that transcatheter-based interventions are effective and typically the first-line treatment for newly diagnosed cases of residual shunt lesions after congenital cardiac surgery. The techniques used demonstrated successful resolution of complex surgical complications, ensuring optimal patient outcomes with minimal risks. These results provided valuable insights into the effectiveness and safety of transcatheter interventions for managing postoperative residual shunt lesions in CHD patients [65].

Simultaneous interventional therapy for compound CHD in children has been shown to be safe and effective. In a study of 155 children, the most common defect was ASD combined with VSD (Figure 3). The therapy resulted in significant improvements in pulmonary gradients and ventricular dimensions, with minimal adverse events [66]. The study included 155 children with compound CHD who underwent simultaneous interventional therapy at the Children's Hospital of Chongqing Medical University from January 2007 to December 2021. The most common type of compound CHD was ASD combined with VSD, which accounted for 32.3% of the patients. The interventional therapy was successful in 151

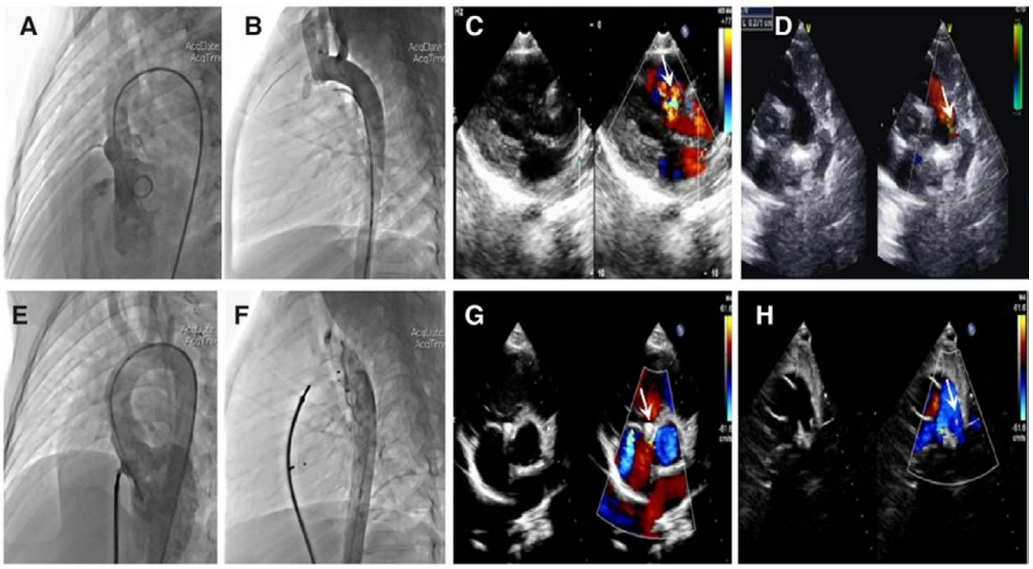

Figure 3: Angiocardiography and echocardiography images in a patient with VSD combined with PDA [66].

out of 155 children, resulting in a success rate of 97.4%. This indicates that the procedure was generally effective for the majority of patients. After the procedure, the pulmonary gradient in patients with pulmonary stenosis significantly decreased from an average of 47.3 mmHg to 15.2 mmHg, which is a statistically significant improvement ($p < 0.05$). In terms of heart dimensions, the right ventricular dimension and left ventricular end-diastolic dimension showed significant reductions within the first month post-procedure for patients with ASD combined with VSD. This suggests that therapy can lead to positive changes in heart structure. There was some mild residual shunts observed in 25 patients (16.1%) immediately after the procedure, but more than half of these shunts resolved spontaneously within six months. The study reported a low incidence of major adverse events, with only four cases (2.58%) noted. These included one patient who required medication for cAVB and three patients who needed surgical intervention due to complications like cardiac erosion and tricuspid valve issues. The follow-up duration averaged 19.5 months, with a maximum of 84 months. Most patients (98.7%) maintained a New York Heart Association class I status, indicating good functional capacity post-intervention. Overall, the findings suggested that simultaneous interventional therapy for combined CHD in children is both safe and effective, with most adverse events being mild and manageable [66].

Traditional surgical interventions, while effective, are associated with higher morbidity and longer recovery times. However, minimally invasive cardiac surgery has emerged as a viable alternative, offering excellent clinical outcomes with reduced risk. A study spanning 25 years demonstrated that minimally invasive techniques, such as ministernotomy and minithoracotomy, resulted in successful corrections with low complication rates and no in-hospital deaths [53]. A total of 1,111 pediatric patients underwent minimally invasive cardiac surgery, which included techniques such as ministernotomy, right anterior minithoracotomy, or right lateral minithoracotomy, between January 1998 and December 2022. All patients achieved successful correction of their CHDs. Importantly, there was no need for conversion to median sternotomy during the procedures, indicating a high level of surgical proficiency and technique. The median length of stay in the intensive care unit was 1 day, with a range of 1 to 2 days. The overall hospital stays averaged 5 days, with a range of 4 to 6 days. This suggested a quick recovery process for the patients. The study reported no in-hospital deaths among the patients. Additionally, the rate of major complications was relatively low at 3%, affecting 33 out of the 1,111 patients. This low complication rate highlights the safety and effectiveness of the minimally invasive approach. The findings supported the conclusion that minimally invasive cardiac surgery, when performed in experienced centers, yields excellent clinical results without additional risks compared to traditional median sternotomy. This has led to the recommendation that minimally invasive techniques should be considered the gold standard for treating many CHDs. In summary, the study demonstrates that minimally invasive cardiac surgery is a safe and effective option for pediatric patients with CHD, with favorable outcomes in terms of surgical success, recovery time, and complication rates [53].

While the advancements in pediatric cardiac interventions for CHDs have significantly improved patient outcomes, challenges remain. The choice between surgical and interventional approaches often depends on the specific defect and patient condition. Moreover, ongoing research and collaborations are crucial for further enhancing treatment strategies and understanding long-term outcomes. Despite the progress, some CHDs still pose substantial risks, underscoring the need for continued innovation and research in this field.

Challenges in Management

Despite advancements in surgical techniques and postoperative care, challenges remain in managing pediatric patients with CHDs (Table 3). Malnutrition is a significant concern, particularly in preoperative patients, as it can adversely affect surgical outcomes [67]. Additionally, the risk of postoperative complications, such as arrhythmias and chylothorax, necessitates careful monitoring and management [68, 69]. These challenges are compounded by the diverse clinical manifestations of CHD, the need for specialized interventions, and the disparities in healthcare access globally. Addressing these challenges requires a multidisciplinary approach, incorporating advances in medical technology, surgical techniques, and global health initiatives. This section delves into the specific challenges and strategies for managing pediatric CHD.

Table 3: Treatment and management approaches for CHDs.

Approach	Description	Examples	Benefits	Challenges
Surgical interventions	Open-heart surgeries to repair defects	Septal defect closure, valve repair	Corrects major structural issues	Risk of complications, lengthy recovery
Catheter-based procedures	Minimally invasive techniques	Balloon angioplasty, stent placement	Reduced recovery time	Limited to certain CHDs
Pharmacological treatment	Medications to manage symptoms and complications	Diuretics, ACE inhibitors	Symptom relief, improves function	May not prevent disease progression
Long-term management	Ongoing care and follow-ups	Lifelong monitoring, lifestyle modifications	Prevents secondary complications	Requires lifelong adherence
Palliative care	Comfort care for non-operable cases	Symptom relief, quality of life support	Enhance patient comfort	Does not address underlying defect
Lifestyle modifications	Dietary and activity recommendations	Low-sodium diet, controlled physical activity	Improves quality of life	Compliance challenges
Cardiac rehabilitation	Supervised exercise and education programs	Post-surgical recovery programs	Enhance recovery and fitness	Limited access in some regions
Psychosocial support	Mental health care and family support	Counseling, support groups	Reduces anxiety, improves well-being	Underutilized in many healthcare settings

- Diverse clinical presentations: CHD can manifest in a wide range of symptoms, from mild to severe, including cyanosis, heart failure, and arrhythmias. This diversity necessitates precise diagnostic approaches to tailor appropriate interventions [70].
- Complex decision-making: The management of CHD involves significant uncertainty, particularly in deciding the timing and type of interventions. This is due to the lack of comprehensive data and the variability in disease progression [71].
- Anesthetic considerations: Anesthesia in children with CHD, especially those with cyanotic conditions, requires careful management to maintain hemodynamic stability and avoid complications such as hypoxia [72, 73].
- Surgical and interventional advances: The evolution of surgical techniques and interventional cardiology has significantly improved outcomes for children with CHD. Early corrective surgeries and minimally invasive procedures are now standard practices [74].
- Multidisciplinary care: Effective management of CHD often involves a team of specialists, including cardiologists, anesthesiologists, and radiologists, to ensure comprehensive care and optimal outcomes [73].
- Global health initiatives: In developing countries, access to pediatric cardiac care is limited. Initiatives like the World Society for Pediatric and Congenital Heart Surgery aim to establish global standards and improve access to care through education and infrastructure development [75, 76].
- Technological advancements: Future improvements in CHD management are expected from innovations in genetics, bioengineering, and imaging technologies. These advancements aim to enhance diagnostic accuracy and treatment efficacy [74].
- Neurocognitive considerations: As survival rates improve, attention is shifting towards the long-term neurocognitive outcomes of CHD patients. Research is ongoing to understand and mitigate the impacts of CHD on cognitive development [77].

While significant progress has been made in the management of pediatric CHD, challenges remain, particularly in ensuring equitable access to care and addressing the long-term impacts of the disease. The integration of new technologies and global health strategies holds promise for further improving outcomes for children with CHD worldwide. However, the complexity of CHD and the variability in healthcare resources necessitate ongoing efforts to develop tailored, context-specific solutions.

Long-term Care and Transition to Adulthood

As patients with CHDs transition to adulthood, they often require specialized care from adult congenital cardiologists. The development of risk scores and prediction models for adults with congenital heart disease is crucial for optimizing management and improving long-term outcomes [18]. Furthermore, the integration of telehealth and home monitoring programs has shown promise in enhancing follow-up care for these patients [78]. Transition programs have been shown to improve disease-related knowledge and self-management skills among adolescents and young adults with CHD.

A systematic review and meta-analysis found that these programs significantly enhance patients' understanding of their condition and reduce the likelihood of being lost to follow-up, although the certainty of evidence remains low [79]. This study included ten studies with a total of 1,297 participants. These studies compared the effects of transition interventions against control groups, focusing on their impact on healthcare transition for young individuals with CHD. Transition interventions were found to significantly enhance disease-related knowledge among participants. The effect size was measured with Hedge's g = 0.89, indicating a large positive impact (95% CI: 0.29 to 1.48). The interventions also improved self-management skills, with an effect size of Hedge's g = 0.67, which is considered a moderate effect (95% CI: 0.38 to 0.95). One of the critical outcomes was a reduction in loss to follow-up among participants who received transition interventions. The odds ratio for this outcome was 0.41 (95% CI: 0.22 to 0.77), suggesting that those who underwent transition interventions were less likely to disengage from healthcare services. Despite these positive findings, the authors noted that the certainty of evidence for the estimated outcomes was low or very low. This indicates that while the results are promising, they should be interpreted with caution due to the limited data available. The study supports the implementation of transition interventions, highlighting their potential to improve disease knowledge, self-management, and treatment continuity for adolescents and young

adults with CHD. However, the authors caution that the current evidence base is limited, and future research may alter these conclusions as more structured transition interventions are adopted. These results underscore the importance of effective transition programs in enhancing the healthcare experience for young individuals with CHD [79].

Many adolescents with CHD are lost to follow-up during the transition to adult care, with studies indicating a loss rate of up to 31.9% globally. This discontinuity is often linked to the complexity of CHD and regional differences in healthcare systems [80]. Barriers to successful transition include logistical issues such as time, distance, and cost, as well as psychosocial factors like the establishment of new healthcare relationships and the balance of patient autonomy [81]. Successful transition programs involve multidisciplinary care, including cardiologists, nurses, psychologists, and other healthcare professionals, to address the comprehensive needs of CHD patients. This approach helps in educating patients and families, promoting self-management, and ensuring adherence to treatment plans [82].

Conclusion

CHDs remain a significant public health concern, demanding continuous advancements in diagnosis, treatment, and management. The review highlights advance in imaging technologies, surgical techniques, and prenatal screening have improved survival rates and quality of life. However, long-term outcomes still vary, emphasizing the need for standardized post-treatment care and lifelong monitoring. Collaborative research efforts and innovative therapeutic strategies are essential to further enhance patient outcomes.

Future research on CHDs should prioritize precision medicine approaches, leveraging genetic and molecular insights for personalized treatment. The development of minimally invasive surgical and catheter-based interventions could further reduce morbidity. Improved prenatal diagnostic tools, including enhanced fetal imaging and non-invasive genetic screening, hold promise for early intervention. Additionally, longitudinal studies on the psychosocial and neurodevelopmental impacts of CHDs will be vital for comprehensive patient care. Enhanced global collaboration and data-sharing initiatives will drive innovation and improve outcomes in this field.

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Conflict of Interest

None.

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