Review Article

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Fetal cardiac diagnostics in Indonesia: a study of screening and echocardiography

https://doi.org/10.1515/jpm-2025-0037
Received January 23, 2025; accepted March 5, 2025;
published online April 16, 2025

Abstract

Introduction: Congenital heart defects (CHDs) are a leading cause of neonatal morbidity and mortality globally. Accurate prenatal detection is crucial to improving neonatal outcomes. In Indonesia, two primary methods are used: fetal cardiac screening (FCS), which is accessible but limited in sensitivity (40–60 %), and fetal echocardiography (FE), the gold standard with over 90 % sensitivity but limited access due to infrastructural and financial challenges.

Content: This review analyzes Indonesia's diagnostic disparities, highlighting how rural regions rely heavily on FCS, while FE remains restricted to urban centers. Emerging technologies, such as AI-enhanced diagnostics and telemedicine, show promise in bridging gaps by increasing FCS accuracy and extending access to FE through remote consultations.

Summary: AI has the potential to boost FCS sensitivity by up to 30 %, making it an effective preliminary screening tool, while telemedicine platforms connect rural practitioners to urban specialists. However, barriers like insufficient infrastructure, regulatory issues, and limited training hinder widespread adoption.

Outlook: Addressing these gaps requires standardized national protocols, capacity-building initiatives, and public-private partnerships to finance infrastructure and reduce costs. With technology integration and systemic reforms, Indonesia can achieve equitable CHD diagnostics, improving maternal and neonatal outcomes and aligning with global standards.

Keywords: congenital heart defects; fetal echocardiography accuracy; AI in diagnostics; telemedicine

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Introduction

Congenital heart defects (CHDs) are a leading cause of perinatal morbidity and mortality worldwide, underscoring the importance of early and accurate prenatal diagnosis for timely intervention and improved neonatal outcomes [1–7]. In Indonesia, significant disparities in healthcare infrastructure, geographic access, and clinical expertise contribute to inequities in CHD diagnosis, particularly between urban and rural regions [8–16].

As shown in Figure 1, global disparities in prenatal CHD detection rates reflect differences in healthcare infrastructure, access to fetal echocardiography (FE), and standardized protocols [12–31]. Indonesia's rate of 30 % underscores the critical need for interventions targeting urban-rural gaps and technological integration [8, 12–15, 30].

Two primary methods are used for prenatal CHD detection in Indonesia: fetal cardiac screening (FCS) and fetal echocardiography (FE). FCS, which relies on the four-chamber view, is widely accessible and cost-effective but has limited sensitivity (40–60 %) due to its dependence on operator skill [23–29]. In contrast, FE, recognized as the global gold standard, offers diagnostic accuracy exceeding

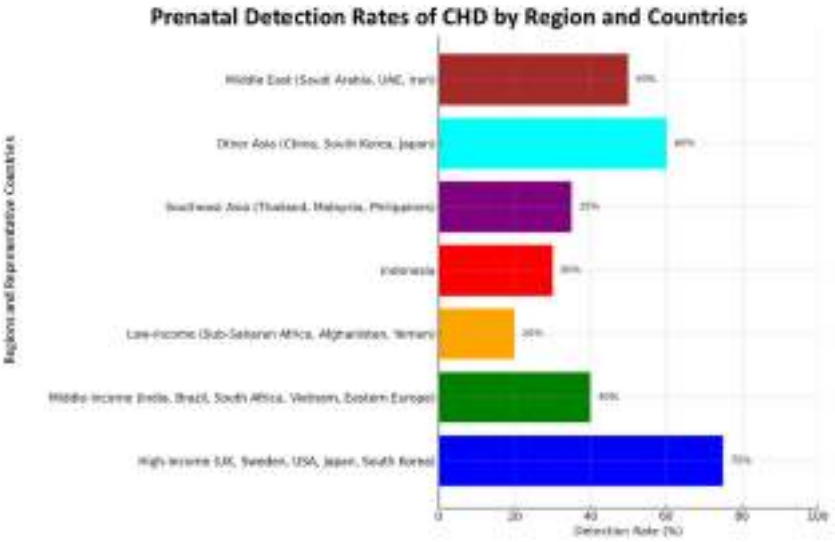

Figure 1: This diagram compares the prenatal detection rates of congenital heart defects (CHDs) across different regions and income-level classifications worldwide. High-income countries such as the UK, Sweden, and the USA achieve the highest detection rates (75 %) due to advanced healthcare infrastructure, widespread access to fetal echocardiography (FE), and standardized protocols. In contrast, low-income countries like those in Sub-Saharan Africa and Afghanistan demonstrate significantly lower detection rates (20 %), primarily due to resource limitations, insufficient training, and lack of access to specialized equipment. Indonesia, categorized separately, has a detection rate of 30 %, reflecting its intermediate position between low- and middle-income nations, with urban-rural disparities impacting diagnostic access. The diagram highlights the stark inequities in prenatal CHD diagnostics globally, underscoring the need for technological innovations and policy reforms to address these gaps [1, 9, 29, 43, 50–60, 72–79].

90 % and is essential for detecting complex anomalies such as transposition of the great arteries (TGA) and hypoplastic left heart syndrome (HLHS) (Figure 2) [30–35]. However, FE remains largely confined to urban tertiary centers due to financial constraints, inadequate infrastructure, and a shortage of trained specialists [36–40].

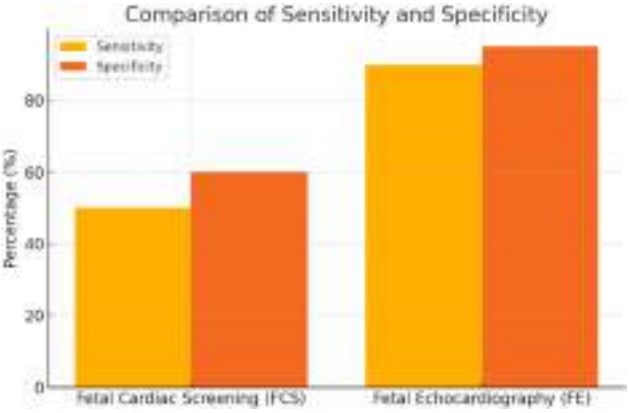

Figure 2: This diagram compares the sensitivity and specificity of fetal cardiac screening (FCS) and fetal echocardiography (FE) in detecting congenital heart defects (CHDs). FCS demonstrates lower sensitivity (approximately 40 %) and specificity (around 60 %), indicating limited accuracy, particularly for complex anomalies. In contrast, FE shows significantly higher sensitivity and specificity (above 90 %), establishing it as the gold standard for prenatal cardiac diagnostics with superior reliability and diagnostic precision [1, 9, 35].

Emerging technologies like artificial intelligence (AI)-enhanced screening and telemedicine offer promising solutions to address these gaps [25, 26, 41–47]. AI can improve the sensitivity of FCS by minimizing operator dependency and increasing diagnostic accuracy, while telemedicine bridges rural practitioners with urban specialists for real-time consultations [25, 26, 33, 34, 43, 48–60]. Research has shown that AI can transform prenatal screening outcomes by achieving diagnostic precision on par with human experts [25, 26, 81, 82].

When combined with policy reforms, standardized protocols, and capacity-building initiatives, these technological advancements could reduce diagnostic disparities and significantly improve perinatal outcomes in resource-limited settings [61–73]. This review examines diagnostic challenges in Indonesia, the role of emerging technologies, and policy recommendations to ensure equitable access to CHD diagnosis and treatment [74–82].

Methods

This review followed a systematic, iterative approach to synthesize insights into fetal cardiac screening (FCS) and fetal echocardiography (FE) across maternal-fetal medicine (MFM) centers in Indonesia, with a focus on addressing diagnostic disparities.

Search strategy and study selection

A comprehensive literature search was conducted using databases, including PubMed, Scopus, Web of Science, and Indonesian repositories. The search covered studies published between January 2010 and January 2025, using keywords such as “fetal cardiac screening,” “fetal echocardiography,” and “congenital heart defects.” Language filters and contextual criteria were applied to ensure relevance to Indonesian settings.

Studies were selected based on the following inclusion criteria:

- Peer-reviewed articles, observational studies, randomized controlled trials (RCTs), and systematic reviews reporting diagnostic accuracy or outcomes in Indonesia.
- Exclusion criteria included studies with limited relevance, non-standardized methodologies, or insufficient data on CHD diagnostics.

Data extraction and synthesis

Key variables extracted included study design, sample size, diagnostic tools used, diagnostic outcomes, and regional healthcare disparities. A thematic synthesis was employed to identify patterns in diagnostic accuracy and access across rural and urban areas. Stakeholder perspectives were collected through semi-structured interviews with maternal-fetal medicine specialists. These review provided qualitative insights into barriers to implementation, infrastructural challenges, and opportunities for integrating emerging technologies like AI and telemedicine.

Ethical considerations

Ethical standards were rigorously maintained throughout the review process, ensuring transparency in study selection and data analysis. The review adhered to established ethical guidelines for secondary research and incorporated feedback from stakeholders to ensure relevance and reliability of the findings.

Results

This study highlights significant disparities in congenital heart defect (CHD) diagnostics both globally and within Indonesia, driven by differences in access to advanced diagnostic tools and healthcare infrastructure.

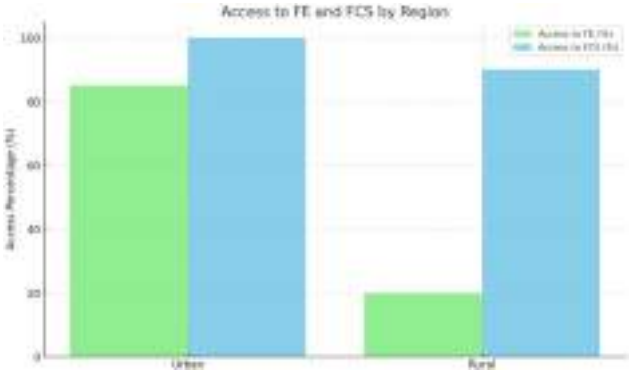

Figure 3: This diagram illustrates the disparity in access to fetal echocardiography (FE) and fetal cardiac screening (FCS) between urban and rural regions in Indonesia. Urban areas in Indonesia show significantly higher access to FE (approximately 80 %), reflecting the concentration of advanced diagnostic facilities and trained specialists, while access to FCS remains nearly universal in both settings. Conversely, rural regions in Indonesia experience limited access to FE (around 20 %), highlighting systemic inequities driven by resource constraints, lack of infrastructure, and insufficient availability of maternal-fetal medicine specialists. This underscores the urgent need for targeted interventions to improve access to FE in rural Indonesia and bridge healthcare disparities [8, 12, 43].

Global perspective on CHD diagnostics

- **Screening Modalities and Diagnostic Accuracy:** Globally, both fetal cardiac screening (FCS) and fetal echocardiography (FE) are critical for prenatal CHD detection. FCS is widely accessible and cost-effective but frequently misses complex anomalies (e.g., transposition of the great arteries) [17, 27, 30]. In contrast, FE – recognized as the gold standard – achieves diagnostic accuracies exceeding 90 % (Figure 2) [10, 23, 27]. Advanced imaging protocols, including the four-chamber and outflow tract views supplemented by 3D/4D imaging and machine learning, enable high-income countries to achieve detection rates up to 87 % (Figure 5) [24–28].
- **Prevalence and Early Detection:** Globally, CHDs affect approximately 1 % of all live births [1, 8, 10, 24, 31]. Early detection of severe conditions, such as hypoplastic left heart syndrome (HLHS) and TGA, remains a challenge in resource-limited settings but is crucial for reducing morbidity and mortality.

Indonesia-specific findings

- **Current Diagnostic Practices:** In Indonesia, while FCS is affordable and widely available, its sensitivity (40–60 %) is limited. FE is predominantly available in

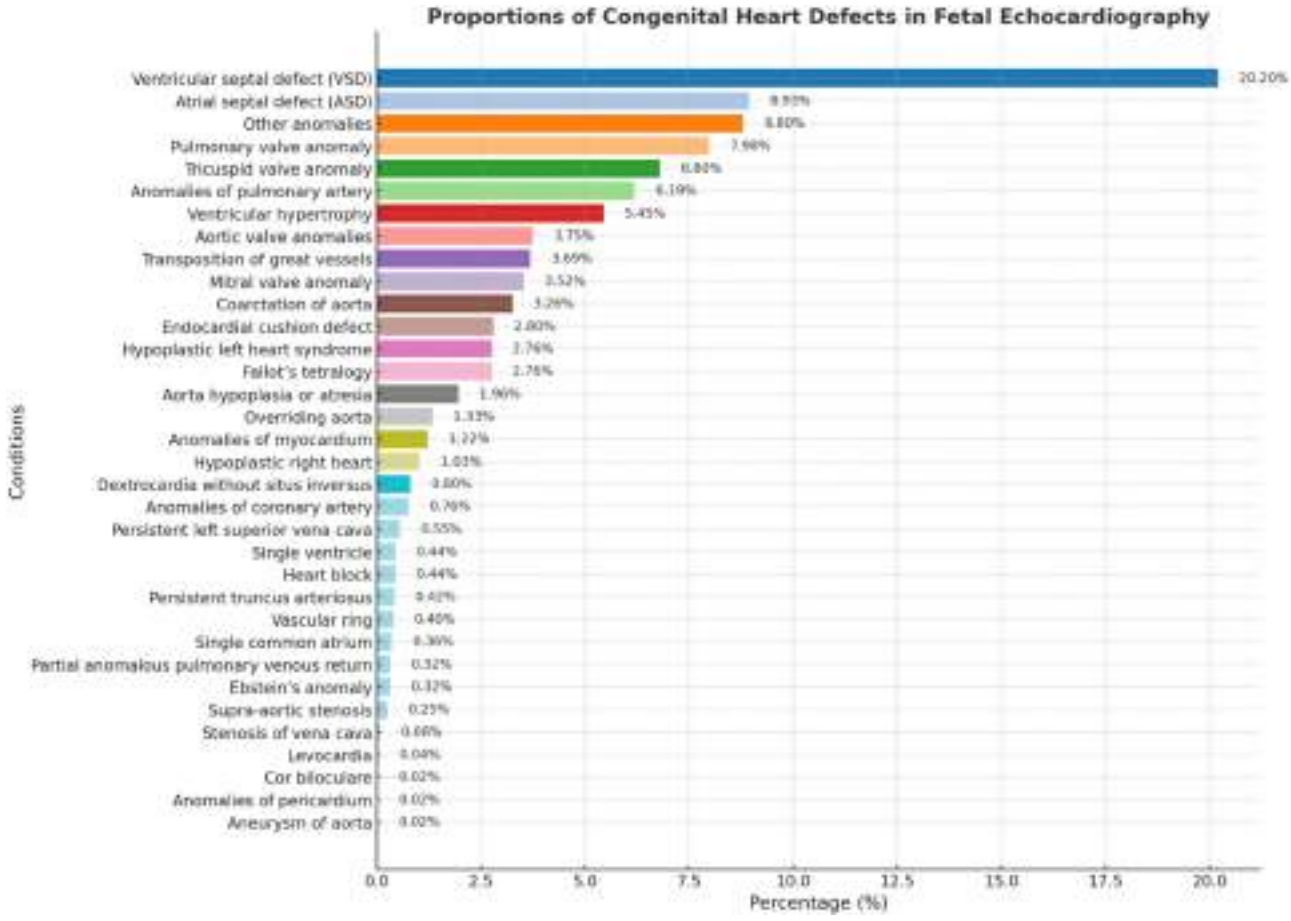

Figure 4: The chart highlights that ventricular septal defect (VSD) is the most common congenital heart defect in fetal echocardiography, accounting for 20.20 % of cases, followed by atrial septal defect (ASD) at 8.93 % and other anomalies at 8.80 %. Pulmonary and tricuspid valve anomalies, along with anomalies of the pulmonary artery, are also relatively frequent, each contributing between 6 and 8%. The remaining conditions, such as coarctation of the aorta and Fallot's tetralogy, occur less frequently, with many rare defects making up less than 1 % of cases [1, 2, 9, 12, 18, 50].

urban centers due to economic, infrastructural, and training limitations, leaving rural regions largely dependent on less effective FCS [10, 18, 32, 41]. This results in overall detection rates around 30 %, far below global benchmarks.

– **Geographical and Socioeconomic Disparities:** Disparities are evident when comparing urban and rural settings. In urban areas, access to advanced imaging and trained specialists brings detection rates closer to global standards. However, only about 20 % of rural practitioners have access to FE vs. 85 % in urban centers (Figure 3) [1, 8, 10, 12, 16, 42]. These differences are driven by financial, logistical, and educational barriers, with rural regions often reporting detection rates below 30 % [18, 37, 52].
– **Local Statistical Insights:** Indonesia reports an estimated 50,000 CHD cases annually, with 25–30 % classified as severe and requiring immediate intervention [14, 38–40]. Furthermore, local FE sensitivity for detecting high-risk cases can be as low as 6 % compared to over 90 % globally [16, 27]. Figure 4 and Table 1 underscore the need for improved diagnostic infrastructure and early detection strategies (Figure 5).

Technological innovations and their role

– **Advances in Diagnostic Tools:** Technological advancements such as AI-enhanced FCS and telemedicine are transforming CHD diagnostics. AI-based improvements have been shown to increase FCS sensitivity by up to 30 %, reducing operator dependency, while telemedicine enables real-time consultations between rural practitioners and urban specialists (Figure 6) [25, 26, 32–34, 81, 82]. Portable ultrasound devices further

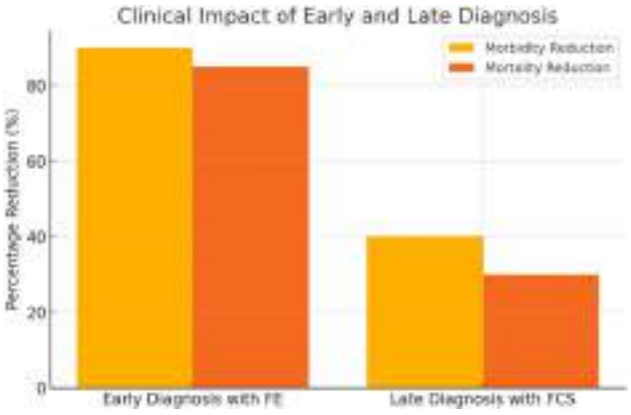

Figure 5: This diagram illustrates the clinical impact of early vs. late diagnosis of congenital heart defects (CHDs) on a global scale, including Indonesia. Early diagnosis using fetal echocardiography (FE) achieves significant reductions in morbidity and mortality (above 80 %), reflecting the advantages of timely interventions enabled by precise and advanced diagnostics. Conversely, late diagnosis through fetal cardiac screening (FCS) results in lower reductions in morbidity and mortality due to the delayed detection of complex anomalies and limited opportunities for early treatment. While this trend is observed globally, it is particularly relevant to Indonesia, where disparities in access to FE further exacerbate the challenges of achieving early diagnosis in rural areas. This emphasizes the need for targeted investments in FE accessibility to improve prenatal and perinatal outcomes in Indonesia and similar resource-constrained settings worldwide [11, 12, 28, 38, 49, 50, 57–59].

extend advanced diagnostic capabilities into underserved regions [51, 55].

– **Local Implementation and Challenges:** In Indonesia, pilot programs integrating AI with portable diagnostic tools have demonstrated improved detection rates in rural areas [48, 61]. Nonetheless, challenges related to infrastructure, cost, and regulatory frameworks persist, necessitating sustained investments and coordinated policy measures [18, 52, 60].

Maternal-fetal medicine centers and access disparities

– **Global vs. Local Access:** Maternal-fetal medicine (MFM) centers globally achieve diagnostic sensitivities exceeding 90 % [23, 27, 50]. In Indonesia, however, these centers are primarily concentrated in urban tertiary hospitals, leaving rural regions to rely on FCS (Figure 3) [16, 28, 38–43, 47–59, 72–77]. Expanding MFM centers through telemedicine and portable technologies – as well as targeted training for general obstetricians – is essential for equitable access to high-quality prenatal diagnostics.

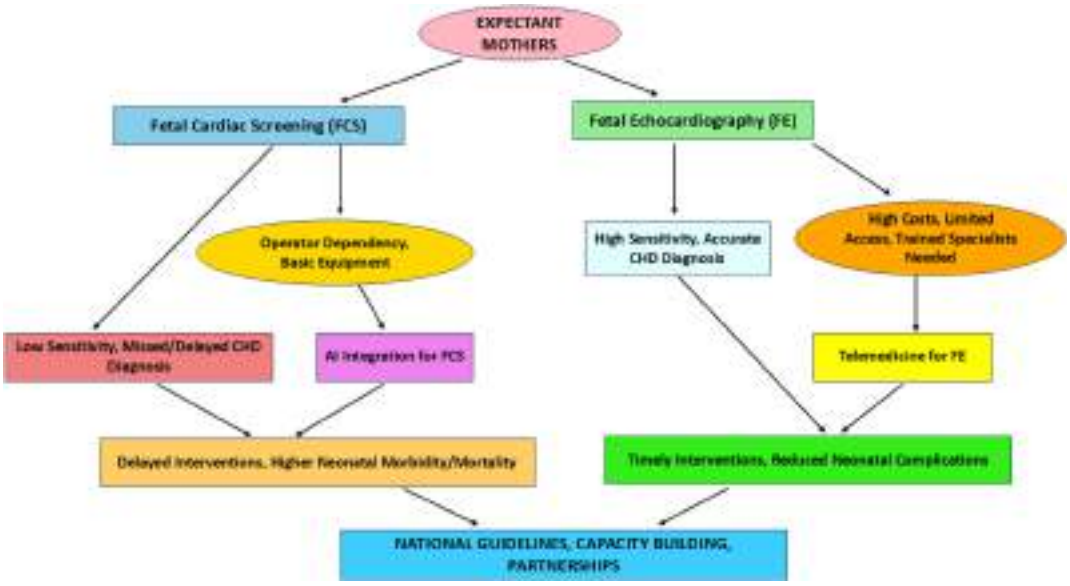

Figure 6: This flowchart outlines a strategic plan for improving prenatal congenital heart defect (CHD) diagnostics in Indonesia, focusing on the roles of fetal cardiac screening (FCS) and fetal echocardiography (FE). It emphasizes the need to address the limitations of FCS, such as operator dependency and low sensitivity, by integrating AI to enhance diagnostic accuracy, while simultaneously tackling the barriers to FE, including high costs, limited access, and a lack of trained specialists, through telemedicine. The flowchart highlights how the current reliance on FCS often leads to delayed interventions and higher neonatal morbidity and mortality, whereas FE enables timely, accurate diagnosis and reduces neonatal complications. The central recommendation involves the establishment of national guidelines, capacity-building programs, and public-private partnerships to ensure equitable access to high-quality prenatal care. This plan reflects a comprehensive approach to harmonizing advanced technology with systemic reforms, aiming to improve maternal-fetal health outcomes across Indonesia [1, 9, 11, 18].

Policy and future directions

- **Strategies for Improvement:** Countries with successful CHD screening programs have implemented unified protocols, robust funding, and comprehensive training initiatives [18, 50]. In Indonesia, adopting standardized national guidelines that integrate FCS and FE (Figure 6) is critical. Additional strategies include:
  - Increasing investments in healthcare infrastructure, particularly in rural areas [36, 41].
  - Providing financial subsidies and incentives to reduce economic barriers [16, 32].
  - Promoting AI and telemedicine innovations through public-private collaborations [29, 48].
- **Policy Recommendations:** Table 2 outlines key recommendations that include the integration of advanced technologies, financial support mechanisms, and training programs. By addressing these systemic challenges, Indonesia can align its healthcare system with global standards and improve maternal and neonatal outcomes [11, 18, 60].

Discussion

Diagnosing congenital heart defects (CHDs) in Indonesia involves a complex interplay of clinical, infrastructural, and policy challenges. Although fetal cardiac screening (FCS) is widely available due to its affordability and accessibility, its limited sensitivity (40–60 %) underscores the need for advanced diagnostic tools like fetal echocardiography (FE), which achieves over 90 % diagnostic accuracy but remains largely inaccessible in many rural regions due to financial and logistical barriers (Figure 2) [23, 24, 33]. Emerging technologies – including AI-enhanced FCS and telemedicine – offer promising solutions to bridge these gaps. However, achieving equitable access requires systemic reforms, standardized protocols, capacity-building efforts, and sustainable funding mechanisms [16, 18, 35]. This section discusses fetal heart screening protocols, disparities in diagnostic access, the role of technological innovations, and policy recommendations for improving CHD outcomes in Indonesia.

Table 1: Comparison of congenital heart defects: global vs. Indonesia ([a]).

Aspect	Global	Indonesia
Prevalence	8–10 per 1,000 live births	8 per 1,000 live births
High-risk detection via FE	~90 %	~6 %
Treatment capacity	Comprehensive	1,600 cases/year
Most common CHDs	VSDs, ASDs, PDA	VSDs, ASDs, PDA
Severe CHDs requiring surgery	~25–30 %	~25–30 %
Mortality	Low with early treatment	High in rural areas

([a]) Despite a similar CHD prevalence (8–10 per 1,000 live births), Indonesia's low fetal echocardiography detection rate (6 % vs. 90 % globally) and limited treatment capacity (1,600 cases/year) result in higher rural mortality, highlighting the urgent need for enhanced diagnostic and treatment infrastructure [1, 2, 9, 12–14, 50]. VSD, ventricular septal defect; ASD, atrial septal defect; FE, fetal echocardiography; CHD, congenital heart defects.

Table 2: Policy recommendations data ([a]).

Recommendation	Expected impact
Mandate universal CHD screening with FCS and FE	Improved diagnostic precision and equity
Develop training programs for advanced imaging	Increased availability of skilled professionals
Encourage public-private partnerships for funding	Reduced financial barriers to accessing FE
Leverage AI and telemedicine to enhance diagnostics	Better accessibility in rural and underserved areas

([a]) Policy recommendations for improving CHD diagnostics include universal screening with FCS and FE, training programs to expand skilled professionals, public-private partnerships to reduce financial barriers, and leveraging AI and telemedicine to enhance rural access, collectively aiming to establish a more equitable and effective diagnostic framework [9, 11, 18, 27].

Fetal heart screening protocols

A comprehensive fetal heart examination is crucial for detecting CHDs, especially in resource-limited settings where FCS is often the primary screening tool [23, 24, 33]. As illustrated in Figure 7, the sequential imaging technique begins at the upper abdomen and progresses cephalad, allowing the operator to visualize the key cardiac structures needed for accurate diagnosis. This Figure serves as a visual roadmap for practitioners, emphasizing the systematic approach required for thorough screening. Figure 8 details the five critical axial planes essential for fetal heart screening. Each plane is designed to capture specific cardiac and vascular structures, such as the four-chamber view and outflow tracts. This diagram not only clarifies the step-by-step process but also highlights the regions where anomalies like tetralogy of Fallot or truncus arteriosus can be detected [3, 4, 7, 9, 11, 23, 24]. Figure 13 shows examples of detected anomalies including ventricular septal defect (VSD), truncus arteriosus, cardiomegaly, and hypoplastic left heart syndrome (HLHS) [9, 11, 23, 24]. Early detection of these anomalies is crucial for improving perinatal outcomes through timely intervention [27, 28, 76].

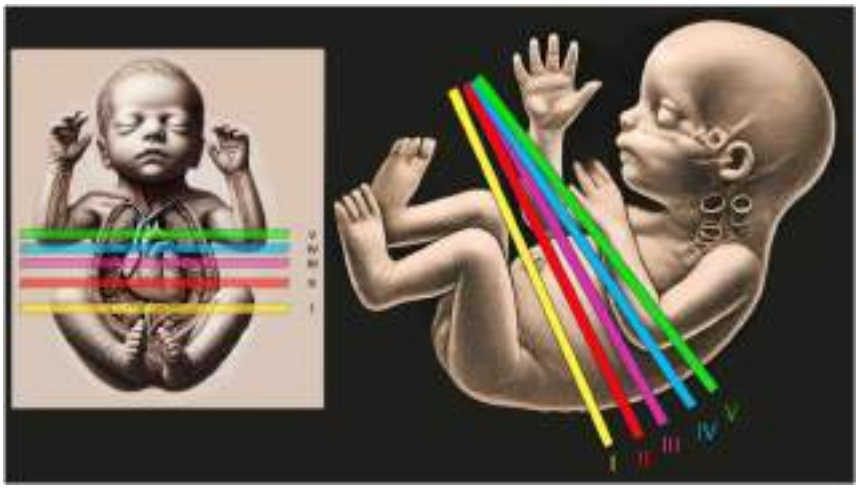

Figure 7: Method for examining the fetal heart using sequential imaging planes. (I) The axial view of the upper abdomen is observed initially. (II) By shifting and angling the transducer upward in a cephalad direction, the four-chamber view is captured through an axial imaging plane across the fetal chest. Continuing to move the transducer further cephalad from the four-chamber view toward the fetal head reveals the outflow tract and major vessel views in sequence: (III) the left ventricular outflow tract view; (IV) the right ventricular outflow tract view along with variations of the three-vessel view; and (V) the three-vessel-and-trachea perspective [3–5, 9, 11, 17].

Ideal screening period

The optimal screening window is between 18 and 22 weeks of gestation [2–5, 7–11]. Scans performed closer to 20–22 weeks tend to reduce the need for follow-up evaluations compared to earlier scans, though early screenings in the late first or early second trimester can help detect critical abnormalities when markers such as increased nuchal translucency are present [31].

Evaluating fetal situs and the four-chamber view

Evaluating fetal situs involves identifying the right and left sides to establish normal abdominal and cardiac orientation; transverse ultrasound sweeps confirm that both the stomach and heart are correctly positioned. Abdominal situs verification checks that the stomach, descending aorta, and inferior vena cava align properly relative to the spine, typically correlating with atrial situs solitus. In the four-chamber view, the heart should occupy about one-third of the chest cavity with a long-axis orientation of roughly 45° (±20°); structural deviations may indicate underlying CHDs, necessitating further imaging [3, 4, 9, 11, 24]. Figures 9–11, respectively, illustrate the assessment of fetal abdominal situs using grayscale and Doppler ultrasound, evaluation of fetal cardiac position and axis, and key components of the four-chamber view essential for detecting CHDs [9, 11, 16, 18, 23, 24]. One such structural anomaly is an atrial septal defect (ASD), which may be suspected in the four-chamber view and confirmed through advanced modalities such as STIC 4D ultrasound. Figure 12 illustrates a clear case of ASD, showing a persistent opening in the atrial septum that enables abnormal blood flow between the left and right atria. This dynamic imaging provides precise anatomical detail – including the size and location of the defect – and plays a crucial role in prenatal diagnosis, perinatal risk assessment, and postnatal management planning (Figure 13).

Evaluating outflow tracts and major vessels

Outflow tract imaging enhances CHD detection by visualizing critical structures that might not be apparent in the four-chamber view alone (Figure 8). A cephalad transducer sweep from the four-chamber view enables visualization of the aortic and pulmonary outflow tracts (LVOT and RVOT), ensuring size symmetry, while supplementary views such as 3VV and 3VTV assess spatial relationships among major vessels to identify potential anomalies like double-outlet right ventricle or truncus arteriosus [9, 11, 24].

Disparities in CHD diagnostics in Indonesia

Urban-rural disparities in CHD diagnostics persist. Figure 3 clearly illustrates that while approximately 85 % of urban practitioners utilize FE, only about 20 % in rural areas have access to this advanced tool. Furthermore, Figure 5 compares

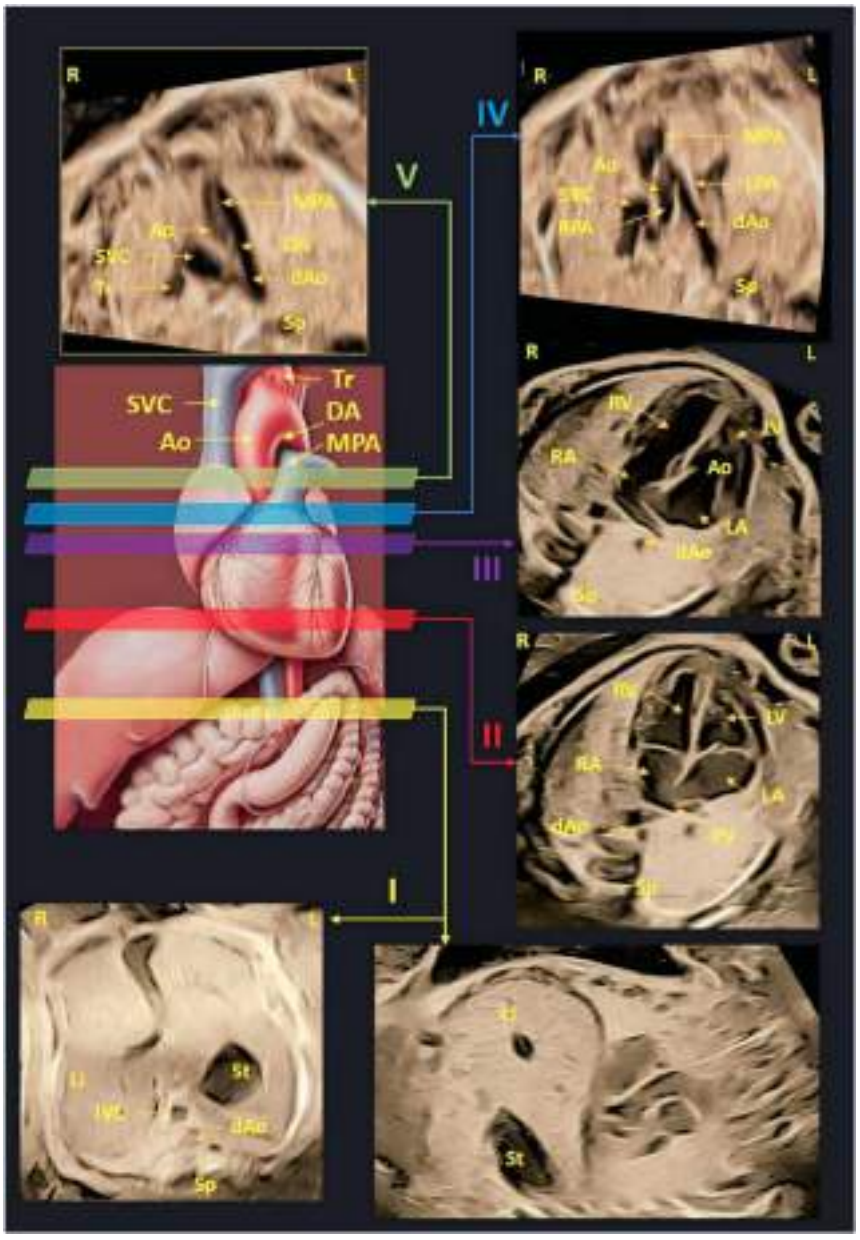

Figure 8: Five axial planes essential for optimal fetal heart screening, as illustrated in Figure 7. The diagram highlights the trachea, heart, major vessels, liver, and stomach, with the five insonation planes delineated by polygons, corresponding to the grayscale ultrasound images provided. (I) **Lowest (caudal) plane**, showing the fetal stomach (St), transverse section of the descending aorta (dAo), inferior vena cava (IVC), spine (Sp), and liver (Li). (II) **four-chamber view** of the fetal heart, depicting the right and left ventricles (RV, LV) as well as atria (RA, LA), with the foramen ovale (FO) and pulmonary veins (PV) positioned to the right and left of the dAo. (III) **Left ventricular outflow tract (LVOT) view**, demonstrating the proximal segment of the ascending aorta (Ao), along with the LV, RV, LA, RA, and a transverse section of the dAo. (IV) **A slightly higher view**, showing the right ventricular outflow tract (RVOT) with the main pulmonary artery (MPA) branching into the right (RPA) and left (LPA) pulmonary arteries, along with cross-sections of the Ao and dAo. (V) **Three-vessel and trachea (3VT) view**, showcasing the superior vena cava (SVC), MPA, ductus arteriosus (DA), transverse arch of the aorta (extending from proximal Ao to dAo), and the trachea (Tr). L represents left, and R represents right [3–5, 9, 11, 17].

global detection rates, showing that high-income countries can achieve detection rates up to 87 %, whereas low-resource settings, including rural Indonesia, often report rates below 30 %. These visual aids underscore the critical need for targeted interventions in under-resourced regions. Reducing these disparities is essential to improving neonatal outcomes and minimizing preventable CHD-related mortality [22, 38, 39, 47–50].

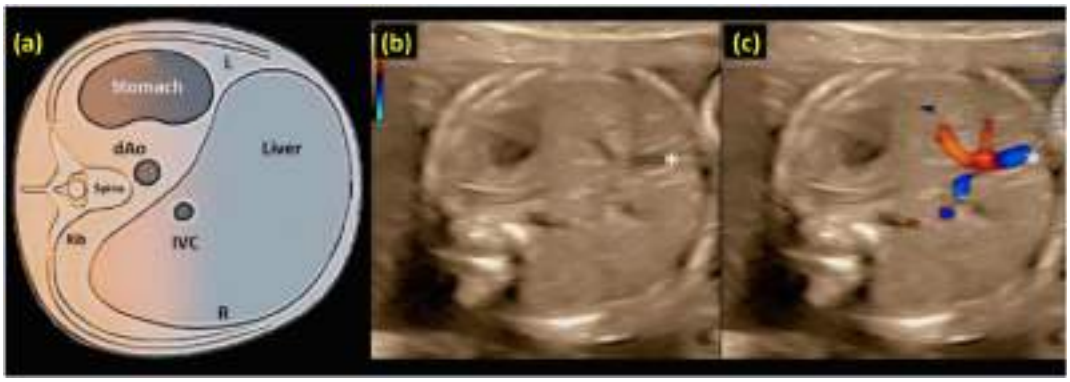

Figure 9: A schematic diagram (a), along with grayscale (b) and color Doppler (c) ultrasound images, depicting an axial view of the fetal upper abdomen. (a) The transverse view of the fetal abdomen is used to assess abdominal situs. After establishing fetal laterality based on the position *in utero*, the stomach should be observed on the left side of the fetus, while the descending aorta (dAo) and inferior vena cava (IVC) are located to the left and right of the spine, respectively. (b, c) A short segment of the umbilical vein (*) is visible in the center of the liver. L and R indicate left and right [3–5, 9, 11, 17, 24, 65, 66].

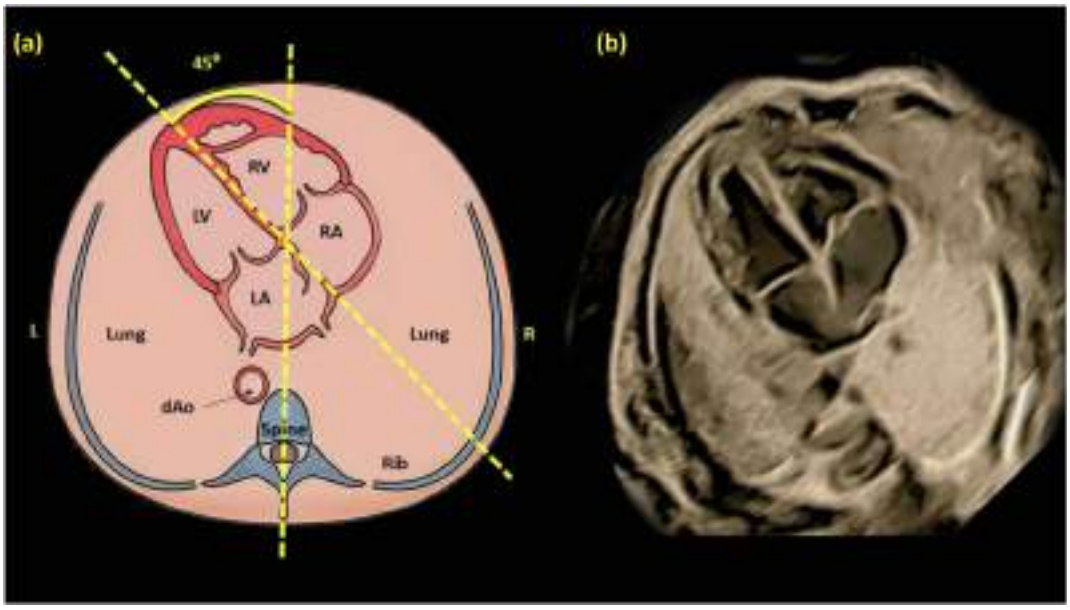

Figure 10: Illustrates the determination of cardiac position and axis through a schematic diagram (a) and a corresponding grayscale ultrasound image (b). An imaginary line is drawn from the spine at the back to the sternum at the front, dividing the thorax into two equal halves, left (L) and right (R). In a normal fetal heart, the majority of the heart is located on the left side, with the cardiac apex oriented towards the left at an angle of 45±20° relative to the anteroposterior axis of the chest. dAo refers to the descending aorta; LA, left atrium; LV, left ventricle; RA, right atrium; and RV, right ventricle [3–5, 9, 11, 24, 65, 66].

Technological innovations and systemic solutions

AI-enhanced FCS and telemedicine offer significant opportunities to improve diagnostic accuracy in prenatal CHD detection. Figure 6 provides a detailed flowchart illustrating how AI tools are integrated with telemedicine networks to facilitate real-time consultations between rural practitioners and urban specialists – this integration has been shown to reduce operator dependency and improve sensitivity by up to 30 % [29, 33, 34]. The diagram visually reinforces the potential impact of these innovations in bridging the urban-rural diagnostic gap [25, 26, 33, 34].

Recent studies further strengthen this approach. Pietrolucci et al. have demonstrated that AI tools, such as Heartassist™, can achieve diagnostic precision comparable to that of human experts, thereby minimizing operator variability [81]. Similarly, Rizzo et al. highlighted the

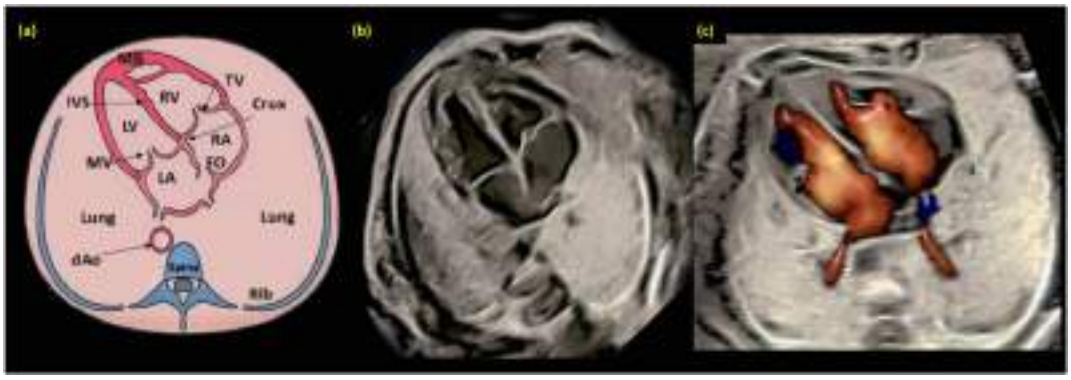

Figure 11: Shows a schematic drawing (a) and accompanying grayscale (b) and color Doppler (c) ultrasound images of the four-chamber view. Essential features of a normal four-chamber view in the second trimester include the heart occupying no more than one-third of the chest area, right- and left-sided structures being nearly equal in chamber size and wall thickness, a patent foramen ovale (FO) with its valve in the left atrium (LA), an intact cardiac "crux" with normal offset of the two atrioventricular valves, and an unbroken interventricular septum (IVS). In (a) and (b), the morphological right ventricle (RV) is identified by the presence of the moderator band (MB) and tricuspid valve (TV), with the septal leaflet inserting into the septum at a more apical position compared to the mitral valve (MV) insertion (normal offset). Pulmonary veins (PV) are also observed entering the LA. In the color Doppler image (c), two distinct blood inflows into the ventricles during diastole are visible. dAo refers to the descending aorta; IAS, interatrial septum; L, left; LV, left ventricle; R, right; RA, right atrium [3–5, 9, 11, 24, 65, 66].

effectiveness of AI-based image analysis in streamlining prenatal diagnostics, emphasizing its role in enhancing overall screening accuracy [82].

Despite these promising advances, scaling AI and telemedicine solutions faces challenges related to infrastructure, cost, and regulatory frameworks. To ensure widespread adoption, Indonesia must develop robust telemedicine networks, implement targeted training programs for rural practitioners, and establish public-private partnerships to support the integration of these technologies [16, 35, 43–45].

Recommendations for addressing diagnostic inequities

To improve CHD diagnostics, the following measures are recommended:

(1) National Screening Guidelines: Develop standardized protocols integrating FCS and FE to ensure consistent diagnostic practices across regions [9, 11, 20].
(2) Capacity Building: Implement training programs focused on simulation-based learning and continuous professional development for sonographers and obstetricians [18].
(3) Leveraging Technology: Scale AI-based diagnostics and telemedicine, supported by regulatory oversight to ensure ethical and equitable implementation [29, 33, 34].
(4) Public-Private Partnerships: Collaborate with private stakeholders to subsidize diagnostic equipment and reduce economic barriers [35].

Enhancing training, quality assurance, and ethical standards

Structured training in portable diagnostic technologies and telemedicine is essential for reducing skill gaps – particularly in rural areas [16]. Centralized accreditation frameworks can help reduce diagnostic variability and improve outcomes [18]. Additionally, policies addressing equitable resource distribution, diagnostic errors, and data privacy are needed to build public trust in new technologies [20].

Policy implications and future directions

To reduce diagnostic inequities, Indonesia should implement transformative policies that include:

– Universal screening guidelines integrating FCS and FE (Figure 6) [35].
– Investment in healthcare infrastructure to expand diagnostic services in rural areas [22].
– Financial incentives and subsidies to reduce the cost burden of advanced diagnostics [33].
– Scaling AI and telemedicine through pilot programs to validate and expand AI-powered solutions [33, 34].

A centralized CHD database can further guide resource allocation and policy decisions, and public awareness campaigns are needed to address cultural barriers to prenatal diagnostics [18, 23].

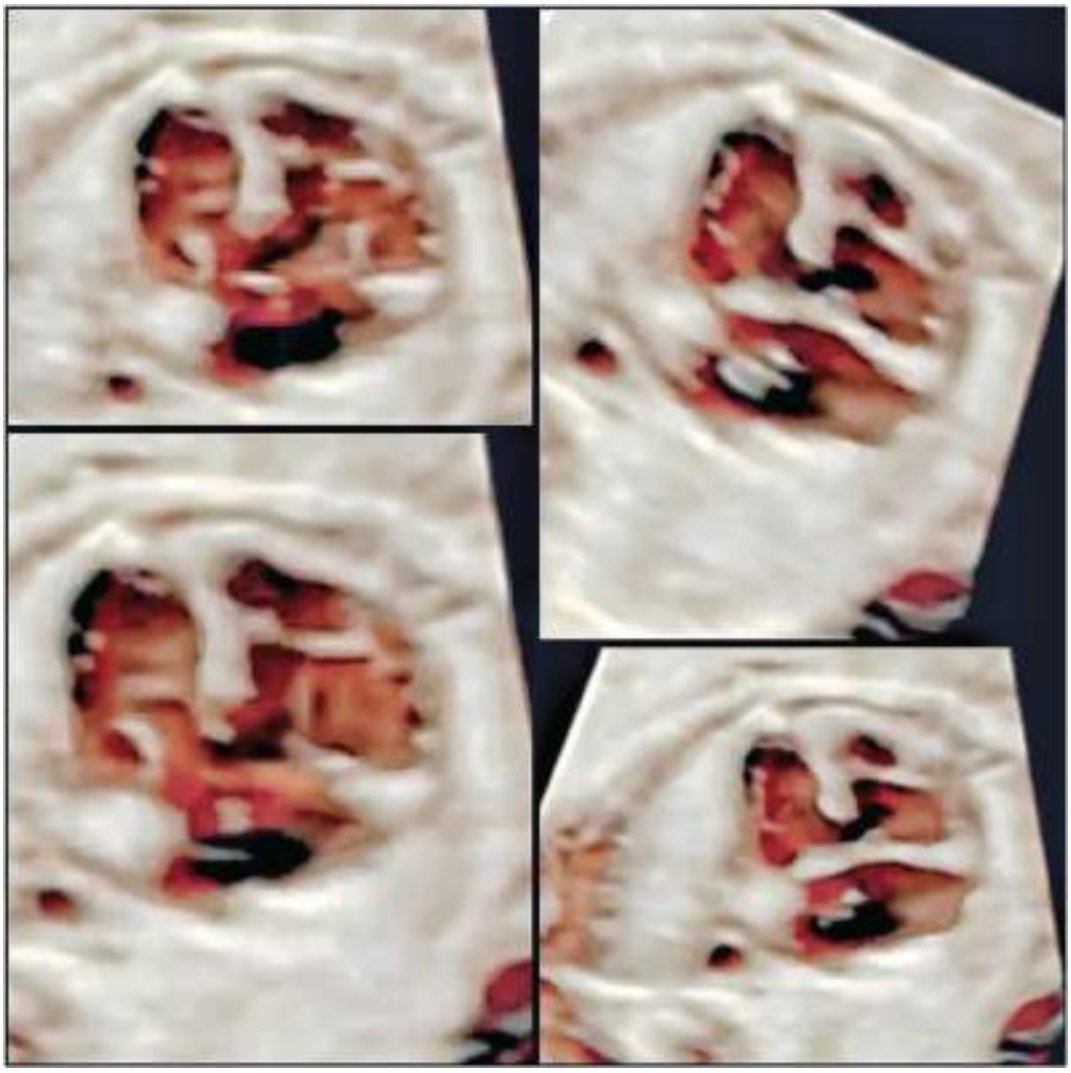

Figure 12: This series of STIC 4D ultrasound images captures the dynamic cardiac anatomy of a fetus in the second trimester, demonstrating a clear case of an atrial septal defect (ASD). The defect is evident as a gap in the atrial septum, the wall that typically separates the left and right atria of the heart. This congenital anomaly allows abnormal blood flow between the atria, potentially impacting the normal oxygenation process and increasing the load on the heart and pulmonary circulation. The images provide a detailed visualization of the defect's size and location, enabling assessment of its potential hemodynamic significance. Such findings are crucial for prenatal diagnosis, postnatal planning, and long-term management, which may involve surgical or interventional correction depending on the severity of the defect [3–5, 9, 11, 44].

Strengths and limitations

This review synthesizes both global and region-specific data to provide actionable insights into improving CHD diagnostics in Indonesia [35]. However, several methodological constraints warrant careful consideration:

- **Reliance on Observational Studies:** A major limitation of this review is its heavy reliance on observational studies. Although these studies offer valuable real-world insights, they are inherently subject to various biases – including selection bias and confounding factors – that may affect the generalizability of the findings. The absence of standardized protocols across these studies further contributes to variability in diagnostic outcomes.
- **Scarcity of Randomized Controlled Trials (RCTs):** The current body of literature includes very few RCTs, which limits our ability to draw causal inferences regarding the effectiveness of screening tools and interventions. RCTs provide a higher level of evidence by controlling for confounding variables and establishing causality; without them, our conclusions are based predominantly on associative findings.
- **Heterogeneity of Study Designs:** The studies reviewed differ in design, patient populations, and outcome

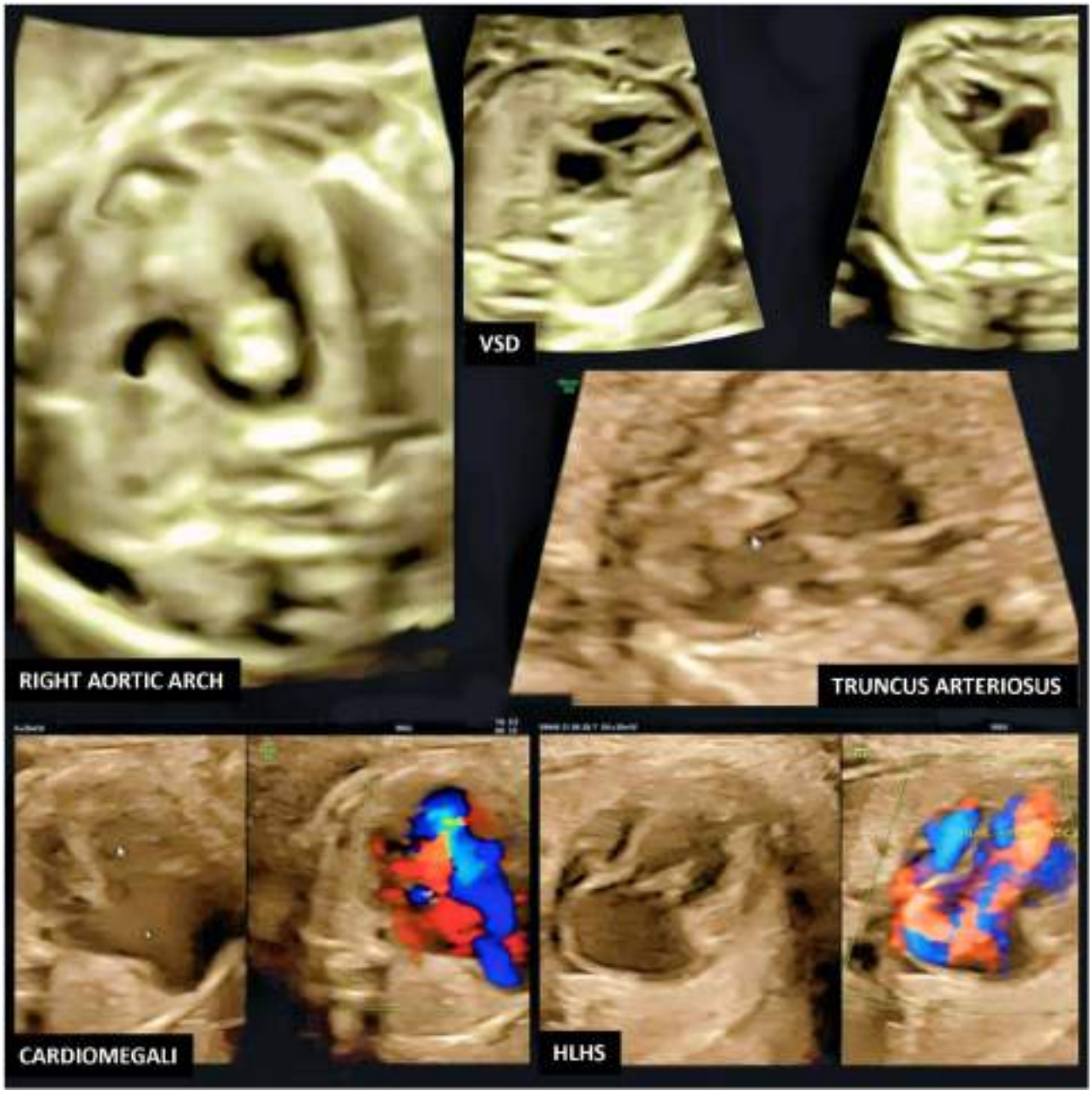

Figure 13: This image illustrates several congenital heart defects (CHDs) diagnosed in the second trimester. The right aortic arch is an anomaly where the aortic arch, typically positioned on the left, is instead on the right, often associated with other cardiac or chromosomal abnormalities. A ventricular septal defect (VSD) is identified as a hole in the wall separating the left and right ventricles, allowing abnormal blood flow and potentially increasing strain on the heart. Truncus arteriosus is a severe condition where a single large vessel arises from the heart instead of the normal two, causing oxygenated and deoxygenated blood to mix and requiring early surgical intervention. Cardiomegaly is visible as an enlarged heart relative to the thoracic cavity, indicating underlying pathology such as structural defects or heart failure. Hypoplastic left heart syndrome (HLHS) shows severe underdevelopment of the left side of the heart, preventing adequate blood flow to the body and necessitating complex surgical care or transplantation. These prenatal findings emphasize the importance of early diagnosis and multidisciplinary planning for postnatal management of CHDs [3–5, 9, 11, 44].

measures. This heterogeneity may lead to inconsistencies when comparing results across different settings, particularly between urban and rural areas. Consequently, caution is needed when extrapolating these findings to broader populations.

– **Implications for Future Research:** To address these limitations, future research should prioritize multicenter RCTs and controlled trials. Such studies would help validate the efficacy of advanced diagnostic techniques (including AI-enhanced FCS and telemedicine)

and assess their long-term impact on perinatal outcomes, especially in resource-limited rural settings [22, 33].

Conclusions

This review highlights significant disparities in prenatal CHD diagnostics in Indonesia, driven by the limited sensitivity of fetal cardiac screening (FCS) and the restricted availability of fetal echocardiography (FE). While FCS is widely accessible, its operator-dependent nature and limited accuracy make it inadequate for detecting complex anomalies. In contrast, FE offers superior diagnostic precision but is largely confined to urban centers due to high costs and infrastructure requirements. These inequities contribute to diagnostic delays and poorer neonatal outcomes, particularly in rural areas. Emerging technologies, including AI-enhanced diagnostics and portable ultrasonography, offer promising solutions to bridge this gap by improving FCS accuracy and extending FE access to underserved regions. However, the successful implementation of these innovations will require comprehensive policy frameworks, investments in infrastructure, and capacity-building programs for healthcare providers. Standardized national screening protocols integrating FCS and FE are essential for ensuring consistency and equitable care. Public-private partnerships can help alleviate financial barriers, while telemedicine platforms can connect rural practitioners to urban specialists, reducing geographical divides. Addressing these challenges will require a coordinated, multifaceted approach combining technological innovation, policy reform, and public education. By adopting these strategies, Indonesia can reduce diagnostic disparities, improve early detection of CHDs, and significantly lower CHD-related morbidity and mortality, ultimately improving maternal and neonatal outcomes.

Acknowledgments: We extend our sincere gratitude to the Ultrasound Working Group of the Indonesian Society of Obstetrics and Gynecology (POGI) and the Indonesian Society of Maternal-Fetal Medicine (HKFM) for their invaluable encouragement and support in the development of this review article.
Research ethics: Not applicable.
Informed consent: Not applicable.
Author contributions: The authors have accepted responsibility for the entire content of this manuscript and approved its submission.
Use of Large Language Models, AI and Machine Learning Tools: None declared.
Conflict interests: The authors state no conflict of interest.
Research funding: None declared.
Data availability: Not applicable.

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