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ORIGINAL ARTICLE

Electrocardiographic Markers as Predictors of Pulmonary Arterial Hypertension in Children with Acyanotic CHD

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ABSTRACT

Introduction: *Pulmonary arterial hypertension (PAH) is a life-threatening complication of uncorrected acyanotic congenital heart disease (CHD). While right heart catheterization (RHC) is the diagnostic gold standard, its invasive nature and limited accessibility in low-resource settings underscore the need for alternative tools. This study aims to evaluate the diagnostic utility of electrocardiography (ECG) markers in predicting PAH severity among children with acyanotic CHD in Bangladesh.* ***Methods & Materials:*** *This cross-sectional analytical study included 83 children (age range: 0.6–17 years) diagnosed with acyanotic CHD at a tertiary care hospital. All participants underwent ECG and cardiac catheterization to assess mean pulmonary artery pressure (mPAP). ECG parameters were analyzed for diagnostic accuracy and correlation with mPAP.* ***Results:*** *PAH was identified in 72.3% of patients, with 40.96% exhibiting severe PAH. R ≥ 7 mm in V1, S ≥ 7 mm in V5, and R V1 + S V5 ≥ 10 mm demonstrated the highest sensitivities (85.0%, 88.3%, and 83.3%, respectively). The composite R V1 + S V5 had the strongest correlation with mPAP (r = 0.68, p < 0.001). All ECG markers assessed showed statistically significant associations with mPAP.* ***Conclusion:*** *ECG parameters—particularly R in V1, S in V5, and their composite—show strong diagnostic value in predicting PAH in children with acyanotic CHD. ECG offers a feasible, cost-effective screening alternative in resource-limited settings.*

Keywords: *Acyanotic congenital heart disease, Pulmonary arterial hypertension, Electrocardiography, Right ventricular hypertrophy, Pediatric cardiology*

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INTRODUCTION

Congenital heart disease (CHD) represents the most common birth defect globally, affecting approximately 9–10 per 1,000 live births [1,2]. Over recent decades, its prevalence has increased, particularly in low- and middle-income countries (LMICs), due to improvements in diagnostic technologies and heightened public and clinical awareness. A systematic review and meta-analysis encompassing 260 studies globally revealed an increasing trend in CHD prevalence, rising to approximately 9.41 per 1,000 live births between 2010 and 2017, with Asia demonstrating some of the highest reported rates [1]. This global scenario underscores CHD's substantial contribution to pediatric morbidity and mortality, particularly in regions with limited access to healthcare infrastructure, timely surgical intervention, and long-term follow-up [3]. In Bangladesh, the reported incidence of CHD markedly exceeds the global average, estimated at approximately 25 per 1,000 live births [4]. Such elevated figures reflect improved detection rates facilitated by more widespread echocardiography availability and better-trained health professionals. Among the pediatric CHD population in Bangladesh, acyanotic lesions predominate, notably ventricular septal defect (VSD), atrial septal defect (ASD), and patent ductus arteriosus (PDA), collectively accounting for approximately 85% of identified cases [5,6]. Untreated or late-treated acyanotic defects significantly increase the risk of progressive pulmonary vascular disease, potentially leading to pulmonary arterial hypertension (PAH), a severe, life-threatening condition characterized by elevated mean pulmonary artery pressure (mPAP) greater than 20 mm Hg [7]. Globally, PAH affects around 1% of the population, with pediatric PAH predominantly arising from uncorrected CHD, particularly in LMICs, where up to 80% of pediatric PAH cases can be directly attributed to delayed diagnosis and lack of timely surgical intervention (8–10). Physiologically, left-to-right shunt lesions, such as those found in acyanotic CHD, lead to chronic pulmonary overcirculation and elevated pulmonary pressures. Persistent pulmonary pressure elevation causes significant remodeling of pulmonary vasculature, including intimal proliferation and medial hypertrophy, ultimately resulting in

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PAH. This chronic hemodynamic strain subsequently imposes severe consequences on the right ventricle, precipitating right ventricular hypertrophy, dysfunction, and eventual failure—a principal cause of mortality in affected children [11]. The gold-standard diagnostic method for PAH remains invasive right heart catheterization (RHC), allowing precise quantification of mPAP and pulmonary vascular resistance. However, RHC is invasive, costly, technically demanding, and carries considerable procedural risks, particularly in pediatric populations and low-resource settings, thereby limiting its practical implementation [12,13]. Echocardiography, while non-invasive, more accessible, and widely adopted, demonstrates inherent limitations due to its operator-dependence, variability in measurement, and reduced specificity in diagnosing complex pediatric cardiac conditions such as PAH in the context of CHD [14,15]. Given these limitations, electrocardiography (ECG) emerges as a promising, accessible, and cost-effective diagnostic modality, widely available even in resource-constrained settings. ECG can effectively capture key cardiac electrophysiological changes characteristic of PAH and right ventricular overload, including right ventricular hypertrophy (RVH), right axis deviation, increased R-wave amplitude in lead V1, altered R/S ratios, and specific ST-T abnormalities [16]. The American Heart Association, American College of Cardiology Foundation, and Heart Rhythm Society have defined specific ECG criteria for RVH indicative of potential PAH, highlighting its potential role in preliminary screening and risk stratification [17,18]. However, despite evidence from adult populations and some mixed-age cohorts, data specifically focusing on ECG predictors of PAH in pediatric acyanotic CHD remain sparse and inadequately characterized, particularly in LMIC contexts like Bangladesh. Existing pediatric studies underscore significant variability in ECG diagnostic accuracy, often due to differences in population demographics, underlying cardiac lesions, and lack of standardized pediatric-specific ECG criteria [19,20]. Therefore, recognizing the significant healthcare gap and urgent need for practical diagnostic tools, the present study aims to evaluate the predictive utility of specific ECG markers in identifying PAH among Bangladeshi children diagnosed with acyanotic CHD. By correlating ECG-derived parameters with catheter-measured mPAP values, this study intends to delineate reliable, accessible ECG indicators for early PAH diagnosis. Such findings could profoundly enhance early detection, facilitate timely therapeutic intervention, and potentially reduce the burden of severe pulmonary vascular disease complications like Eisenmenger syndrome, thereby significantly improving long-term outcomes in pediatric CHD patients in resource-limited settings.

METHODS & MATERIALS

This cross-sectional analytic study was conducted at the Department of Pediatric Cardiology, Bangabandhu Sheikh Mujib Medical University (BSMMU), Dhaka, Bangladesh, over a 12-month period from July 2023 to June 2024. The study aimed to evaluate the diagnostic utility of electrocardiographic (ECG) markers for predicting pulmonary arterial hypertension (PAH) in children diagnosed with acyanotic congenital heart disease (CHD). A total of 83 pediatric patients aged between 2 months and 18 years, who were diagnosed with acyanotic CHD and scheduled for diagnostic cardiac catheterization, were enrolled using a purposive sampling technique. Inclusion criteria consisted of echocardiographically confirmed cases of ASD, VSD, PDA, atrioventricular septal defect (AVSD), and aortopulmonary window. Children with other forms of acyanotic CHD, cyanotic CHD, or those who declined catheterization or participation were excluded. Following ethical approval from the Institutional Review Board (IRB) of BSMMU, written informed consent was obtained from the parents or legal guardians of all participants. Each child underwent a comprehensive clinical evaluation including history taking (noting feeding difficulties, recurrent respiratory infections, and exertional dyspnea) and physical examination. Pre-procedural investigations included complete blood count (CBC), C-reactive protein (CRP), blood grouping, serum alanine aminotransferase (ALT), serum creatinine, chest X-ray, HBsAg, VDRL, prothrombin time (PT), activated partial thromboplastin time (APTT), bleeding time (BT), and clotting time (CT). All patients underwent standard 12-lead ECG in the supine position at a paper speed of 25 mm/sec and voltage of 10 mm/mV. The following ECG parameters were evaluated: QRS axis, P wave amplitude in lead II, R wave amplitude in leads V1 and V5, S wave amplitude in leads V1 and V5, R/S ratio in V1 and V5, the sum of R wave in V1 and S wave in V5, and ST-segment depression in leads II, III, and aVF. ECGs were interpreted independently by two experienced pediatric cardiologists blinded to the catheterization results. Cardiac catheterization was performed under standard procedural protocols. Mean pulmonary artery pressure (mPAP) was measured directly, with PAH defined as mPAP > 20 mmHg at rest based on current clinical guidelines. Patients were divided into PAH and non-PAH groups based on these measurements. Demographic variables (age, gender), anthropometric data (height, weight, body surface area), clinical history, and ECG and catheterization findings were documented for all patients. Statistical analysis was performed using SPSS version 26.0 (IBM Corp., Armonk, NY, USA). Continuous variables were reported as mean ± standard deviation and analyzed using independent sample t-tests or Mann–Whitney U tests. Categorical variables were compared using chi-square or Fisher's exact tests. Receiver Operating Characteristic (ROC) curve analysis was conducted to assess the predictive performance of ECG parameters. A p-value <0.05 was considered statistically significant.

RESULTS

Table I presents the demographic characteristics of the 83 children enrolled in the study. The mean age was 7.03 ± 5.30 years, with a range from 0.6 to 17 years. The average weight and height were 15.16 ± 8.96 kg and 99.03 ± 29.80 cm, respectively. The mean body surface area was 0.62 ± 0.27 m^2. A slight female predominance was observed, with 55.42% of participants being female. The majority of children (83.13%) were from rural areas. [Table I].

Table – I: Demographic Characteristics of the Study Population (*n*=83)

Variable	Value
Age (years)	7.03 ± 5.30 (Range: 0.6–17)
Weight (kg)	15.16 ± 8.96 (Range: 4.0–44.0)
Height (cm)	99.03 ± 29.80 (Range: 42.0–167.0)
Body Surface Area (m^2)	0.62 ± 0.27 (Range: 0.24–1.37)
Gender: Male	37 (44.58%)
Gender: Female	46 (55.42%)

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Residence: Rural	69 (83.13%)
Residence: Urban	14 (16.86%)

Ventricular septal defect (VSD) was the most common lesion, observed in 39.8% of cases, followed closely by patent ductus arteriosus (PDA) at 38.6%. Atrial septal defect (ASD) accounted for 10.8%, atrioventricular septal defect (AVSD) for 9.6%, and aortopulmonary (AP) window was the least common, found in only 1.2% of participants. [Figure I].

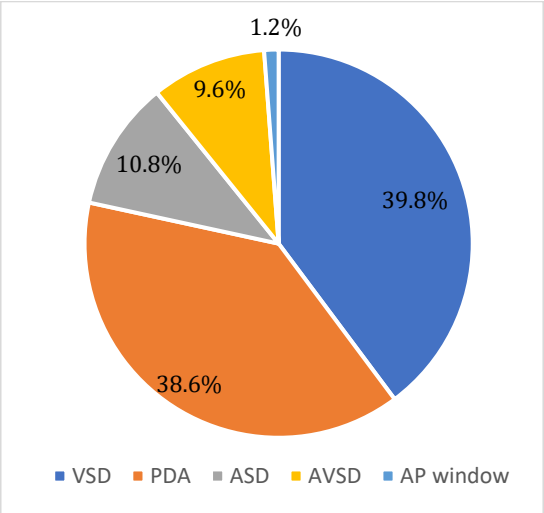


Figure – 1: Distribution of Acyanotic CHD Types Among Study Participants (*n*=83)

Table II shows the distribution of patients according to the severity of pulmonary arterial hypertension (PAH). Severe PAH was the most common, observed in 40.96% of cases, followed by moderate PAH in 19.28% and mild PAH in 12.05%. PAH was absent in 27.71% of the study population. [Table II].

Table – II: Distribution of patients by severity of PAH (*n*=83)

PAH	Frequency	Percentage
Mild PAH	10	12.05%
Moderate PAH	16	19.28%
Severe PAH	34	40.96%
PAH Absent	23	27.71%

Table III presents the distribution of specific ECG parameters among patients with varying severity of pulmonary arterial hypertension (PAH). Most ECG abnormalities were more prevalent in the severe PAH group. Notably, R in V1 ≥ 7 mm was observed in 29 severe cases compared to 8 and 4 in moderate and mild cases, respectively. Similarly, ST segment depression in leads II, III, and aVF, as well as right axis deviation (QRS Axis ≥ 90°), showed a marked increase with increasing PAH severity. This trend suggests a strong association between ECG changes and PAH severity. [Table III].

Table – III: Distribution of Specific ECG Parameters by Severity of PAH (*n*=60)

ECG Parameter	Mild PAH (n=10)	Moderate PAH (n=16)	Severe PAH (n=34)
R in V1 ≥ 7 mm	4	8	29
S in V1 ≤ 2 mm	3	7	26
R/S in V1 ≥ 1	3	7	27
R in V5 ≤ 5 mm	2	6	25
S in V5 ≥ 7 mm	4	8	30
R/S in V5 ≤ 1	2	5	24
R V1 + S V5 ≥ 10 mm	3	6	28
P wave in II ≥ 2.5 mm	1	4	20
QRS Axis ≥ 90°	2	5	24
ST depression in lead II	1	3	15
ST depression in lead III	0	2	14
ST depression in lead aVF	1	3	16

Table IV summarizes the diagnostic accuracy of various ECG parameters in predicting pulmonary arterial hypertension (PAH). Among the parameters, S in V5 ≥ 7 mm showed the highest sensitivity (88.3%) and positive predictive value (91.2%). R in V1 ≥ 7 mm and R/S in V1 ≥ 1 also demonstrated high diagnostic performance, with sensitivities of 85.0% and 81.7%, respectively. Parameters related to ST segment depression showed lower sensitivity and predictive values. Overall, several ECG markers demonstrated good potential for non-invasive prediction of PAH. [Table IV].

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Table – IV: Diagnostic Accuracy of ECG Parameters in Predicting PAH (*n*=60)

ECG Parameter	Sensitivity (%)	Specificity (%)	PPV (%)	NPV (%)
R in V1 ≥ 7 mm	85.0	78.3	90.6	68.4
S in V1 ≤ 2 mm	78.3	73.9	87.0	60.0
R/S in V1 ≥ 1	81.7	76.5	88.5	64.7
R in V5 ≤ 5 mm	76.7	70.0	85.1	58.6
S in V5 ≥ 7 mm	88.3	80.9	91.2	70.8
R/S in V5 ≤ 1	73.3	69.6	84.0	56.5
R V1 + S V5 ≥ 10 mm	83.3	75.6	89.2	65.5
P wave in II ≥ 2.5 mm	66.7	65.2	78.0	51.0
QRS Axis ≥ 90°	70.0	69.6	82.8	55.0
ST depression in lead II	50.0	60.9	72.0	43.0
ST depression in lead III	46.7	58.7	69.0	40.0
ST depression in lead aVF	53.3	63.0	75.0	44.0

Figure 2 shows a scatter plot illustrating the correlation between R-wave amplitude in lead V1 and mean pulmonary artery pressure (mPAP). A positive linear relationship is observed, with higher R-wave values corresponding to elevated mPAP levels. The coefficient of determination (R^2) is 0.399, indicating a moderate correlation between the two variables. [Figure 2].

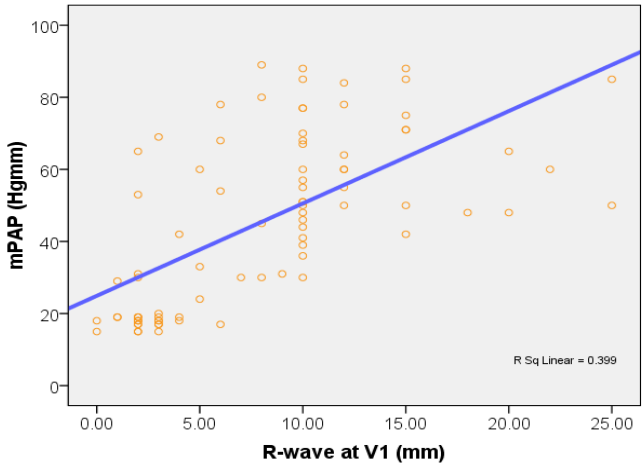
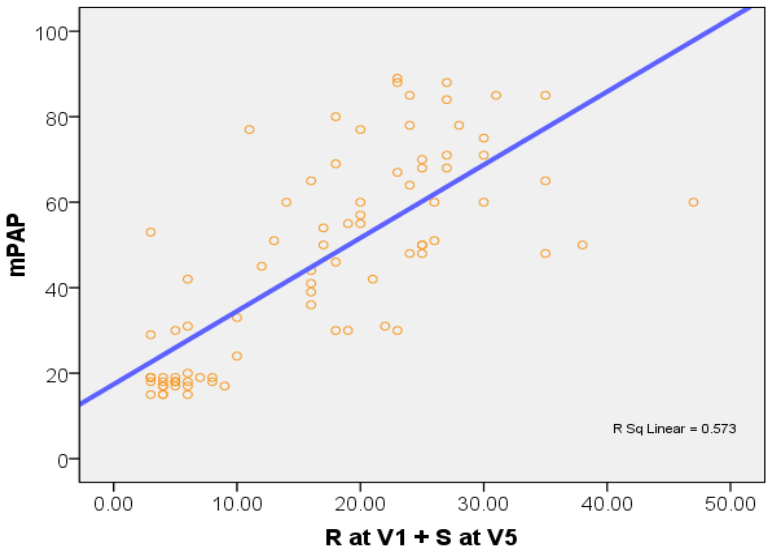


Figure – 2: Correlation Between R Wave in Lead V1 and mPAP

Figure III displays a scatter plot showing the correlation between the composite ECG marker (R wave in V1 + S wave in V5) and mean pulmonary artery pressure (mPAP). A strong positive linear relationship is evident, with increasing composite values corresponding to higher mPAP. The coefficient of determination (R^2) is 0.573, indicating a strong correlation and suggesting this marker is a reliable predictor of PAH severity. [Figure III].



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Figure – 3: Correlation Between Composite ECG Marker (R in V1 + S in V5) and mPAP

Table V presents the correlation between various ECG parameters and mean pulmonary artery pressure (mPAP). The composite marker R in V1 + S in V5 showed the strongest positive correlation (r = 0.68, p < 0.001), followed by S in V5 (r = 0.63) and R in V1 (r = 0.62). Negative correlations were observed for S in V1 (r = –0.55) and R/S in V5 (r = –0.47), indicating inverse relationships. All reported correlations were statistically significant, supporting the utility of specific ECG parameters in predicting elevated mPAP. [Table V].

Table – V: Correlation Between Specific ECG Parameters and Mean Pulmonary Artery Pressure (mPAP)

ECG Parameter	Correlation Coefficient (r)	p-value
R in V1	0.62	<0.001
S in V1	–0.55	<0.001
R/S in V1	0.60	<0.001
R in V5	–0.49	0.001
S in V5	0.63	<0.001
R/S in V5	–0.47	0.002
R V1 + S V5	0.68	<0.001
P wave in II	0.44	0.003
QRS Axis	0.51	0.001
ST depression in lead II	0.39	0.006
ST depression in lead III	0.36	0.009
ST depression in lead aVF	0.40	0.005

DISCUSSION

The present study aimed to evaluate the diagnostic utility of electrocardiographic (ECG) parameters in predicting pulmonary arterial hypertension (PAH) in children with acyanotic congenital heart disease (CHD), using catheterization-derived mean pulmonary artery pressure (mPAP) as the gold standard. Among the 83 enrolled children, the majority were female and from rural settings, with ventricular septal defect (VSD) and patent ductus arteriosus (PDA) representing the most prevalent lesion types. These demographic and diagnostic trends are consistent with findings reported in South Asian pediatric cohorts, where rural representation and high prevalence of VSD and PDA in acyanotic CHD dominate the clinical spectrum [21]. Notably, 72.3% of our cohort demonstrated PAH, with severe PAH present in over 40%—a burden higher than previously documented in global datasets, but not uncommon in tertiary-level referrals from under-resourced settings [22,23]. A central focus of the analysis was the escalation of specific ECG abnormalities with increasing PAH severity. The findings revealed a striking stepwise increment in the presence of right ventricular hypertrophy (RVH) markers, such as R ≥ 7 mm in V1 and S ≤ 2 mm in V1, alongside composite indices like R V1 + S V5 ≥ 10 mm. This parallels observations from Igata et al., who documented that such parameters demonstrate proportional deviation with rising pulmonary pressures and are therefore reliable screening indicators [24]. The high prevalence of ST-segment depression in inferior leads among severe PAH cases also mirrors the regional strain patterns indicative of chronic right ventricular overload, a finding supported by Burns et al., although the low sensitivity of these markers limits their utility as standalone screening tools [25]. When analyzed for diagnostic accuracy, the strongest performers were S ≥ 7 mm in V5 and the composite index R V1 + S V5 ≥ 10 mm, both of which exhibited high sensitivity (88.3% and 83.3%, respectively) and specificity (80.9% and 75.6%, respectively). These results are in concordance with those of other works, who identified these measures as the most robust and clinically reproducible indicators of PAH [24]. Our findings affirm that these ECG metrics maintain a high positive predictive value (PPV > 89%) and moderate negative predictive value (NPV), supporting their use in routine clinical assessment when catheter-based evaluation is not immediately feasible. Correlation analysis further validated these indices, with the strongest association between mPAP and the composite R in V1 + S in V5 (r = 0.68, $p < 0.001$), reinforcing its pathophysiological linkage with elevated right ventricular afterload. These findings align closely with the results from other authors, who independently underscored the prognostic implications of such indices in pediatric populations [24,26]. All assessed ECG parameters showed statistically significant correlations with mPAP, establishing their collective relevance in early PAH detection. Taken together, these findings substantiate the hypothesis that the gradation of ECG changes reflects PAH severity, with several easily measurable markers offering high predictive fidelity. The study supports the incorporation of these parameters—particularly S in V5 and R V1 + S V5—as cost-effective, accessible tools for PAH risk stratification in children with acyanotic CHD, especially in low-resource settings where catheterization access is limited. Nonetheless, while ST-segment depression holds value as a confirmatory marker due to its specificity, its low sensitivity precludes its use for screening. These insights offer practical implications for pediatric cardiology workflows in comparable global contexts.

Limitations of The Study

The study was conducted in a single hospital with a small sample size. So, the results may not represent the whole community.

Conclusion

The present study demonstrates a strong correlation between specific electrocardiographic markers and mean pulmonary artery pressure in children with acyanotic congenital heart disease. Parameters such as R wave amplitude in V1, S wave in V5, and their composite index (R in V1 + S in V5) showed high sensitivity and significant positive correlations with PAH severity measured via right heart catheterization. These findings suggest that ECG, despite its limitations in specificity for early-stage disease, can serve as a valuable, non-invasive screening tool for identifying pediatric patients at risk of developing significant pulmonary arterial hypertension, especially in resource-limited settings like Bangladesh where invasive diagnostics are not readily accessible.

Recommendation

The manuscript presents a well-conducted study highlighting the diagnostic utility of electrocardiographic markers in predicting pulmonary arterial hypertension among children with acyanotic congenital heart disease. The research is timely, methodologically robust, and holds significant clinical relevance, particularly for resource-limited settings. The findings are clearly articulated and supported by appropriate statistical analyses.

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Conflict of interest: None declared
Ethical approval: The study was approved by the Institutional Ethics Committee

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