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Article

Association Between Heart Rate Variability and Ventricular Repolarization Parameters in Children: Insights from 24-Hour Holter Monitoring

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Highlights

What are the main findings?

- Significant maturational increases in HRV parameters across age groups.
- Uncorrected QT interval strongly correlated with HRV indices.
- Sex is a significant independent predictor of QTc.

What are the implications of the main findings?

- Provides age-specific normative percentile charts for HRV in children.
- Facilitates improved clinical interpretation and arrhythmic risk stratification.

Abstract

Background/Objectives: Heart rate variability (HRV) and ventricular repolarization parameters are noninvasive markers of cardiac autonomic regulation and electrical stability. Although these parameters undergo significant maturational changes during childhood, normative data and their physiological interactions in healthy pediatric populations remain insufficiently explored. This study aimed to evaluate the relationship between HRV and ventricular repolarization indices (QT, QTc, QTd, QTcd) in healthy children and to establish age-stratified normative reference values for HRV parameters across four distinct age groups. **Methods:** This cross-sectional study included 254 healthy children (145 males, 57.1%; mean age 12.51 ± 3.55 years, range 5–18 years). All participants underwent 24-hour ambulatory electrocardiographic (Holter) monitoring. HRV parameters (SDNN, SDANN, RMSSD, pNN50, LF, HF, and LF/HF ratio) and ventricular repolarization indices (QT, QTc, QTd, QTcd) were derived. Participants were stratified into four age groups: 5–8, 9–12, 13–15, and 16–18 years. Normative percentile distributions (5th–95th) were generated for all HRV parameters. **Results:** Significant maturational increases were observed in all time- and frequency-domain HRV parameters across the four age groups ($p < 0.001$), accompanied by a decline in heart rate ($r = -0.471$, $p < 0.001$). The uncorrected QT interval showed strong positive correlations with all HRV indices, particularly SDNN ($r = 0.434$, $p < 0.001$) and RMSSD ($r = 0.426$, $p < 0.001$), while heart rate correction (QTc) attenuated these associations. Repolarization heterogeneity (QTd) correlated significantly with SDNN ($r = 0.269$, $p < 0.001$) and HF ($r = 0.186$, $p = 0.004$). Females exhibited significantly higher QTc values ($r = 0.294$, $p < 0.001$) and lower mean HRV values compared to males. Multivariate regression identified sex as the only significant independent predictor of QTc ($\beta = 0.294$, $p < 0.001$). **Conclusion:** Cardiac autonomic modulation, as reflected by HRV, significantly influences ventricular repolarization dynamics in healthy children. The age-specific normative percentile charts established in this study provide a robust physiological reference for pediatric cardiac autonomic and electrophysiological assessment, facilitating improved clinical interpretation and arrhythmic risk stratification in children and adolescents.

Keywords: heart rate variability; ventricular repolarization; pediatric cardiology; autonomic nervous system; Holter monitoring; normative data

1. Introduction

Heart rate variability (HRV) is a well-established, noninvasive marker reflecting the complex autonomic regulation of the cardiovascular system. It provides critical insights into the dynamic balance between sympathetic and parasympathetic activities, where a higher HRV generally signifies a healthy, adaptive autonomic nervous system, while reduced HRV has been consistently linked to increased cardiovascular risk, arrhythmogenesis, and adverse outcomes across various clinical populations [1,2]. HRV parameters derived from 24-hour ambulatory electrocardiographic (Holter) recordings are widely regarded as the gold standard for evaluating cardiac autonomic function, offering a comprehensive assessment of autonomic modulation during daily activities and sleep [3,4].

Ventricular repolarization, a fundamental phase of the cardiac cycle, is represented by electrocardiographic indices such as the QT interval, corrected QT interval (QTc), QT dispersion (QTd), and corrected QT dispersion (QTcd). These parameters provide essential information regarding the duration and spatial heterogeneity of myocardial recovery [5]. Increased dispersion of repolarization, in particular, is considered a marker of electrical instability and has been strongly associated with an increased susceptibility to life-threatening ventricular arrhythmias and sudden cardiac death [6,7]. Consequently, these repolarization markers have become indispensable tools for arrhythmic risk stratification in both adult and pediatric cardiology [8].

The autonomic nervous system plays a pivotal role in modulating ventricular electrophysiology. Sympathetic and parasympathetic influences can significantly alter myocardial repolarization properties, thereby affecting QT interval dynamics and repolarization heterogeneity [9]. While sympathetic stimulation typically shortens the action potential duration and QT interval, parasympathetic activity tends to prolong repolarization and enhance its stability [10]. Several studies in adult populations have demonstrated a significant association between HRV parameters and ventricular repolarization indices, suggesting a profound interaction between autonomic modulation and myocardial electrical stability [11,12]. However, the precise nature of this relationship in the pediatric population remains an area of active investigation.

Data regarding the relationship between HRV and ventricular repolarization parameters in children and adolescents are currently limited. Previous research in this field has predominantly focused on specific patient groups, such as those with obesity, metabolic syndrome, or congenital heart diseases, where autonomic dysfunction is often a confounding factor [13,14]. Since cardiac autonomic regulation and ventricular electrophysiology undergo significant maturational changes from childhood through adolescence, establishing the relationship between these parameters in healthy individuals is crucial [15,16]. Although several studies have examined HRV or ventricular repolarization parameters separately, data evaluating the association between autonomic modulation and repolarization heterogeneity using 24-hour Holter recordings in healthy pediatric populations remain scarce. Furthermore, there is a pressing clinical need for age-stratified normative reference values for HRV parameters to accurately interpret autonomic function in the pediatric age group [17].

Therefore, the present study aimed to evaluate the relationship between HRV parameters and ventricular repolarization indices (QT, QTc, QTd, and QTcd) obtained from 24-hour Holter recordings in a cohort of healthy children. In addition, we sought to determine age-specific normative reference values for HRV parameters in this population. By clarifying the physiological interactions between autonomic modulation and cardiac repolarization during development, this study aims to provide a robust framework for clinical assessment and future research in pediatric electrophysiology.

2. Methods

2.1. Study Design and Population

This cross-sectional observational study was conducted at the Pediatric Cardiology Department of Karabuk University Karabuk Training and Research Hospital between June 2025 and March 2026. The study protocol was approved by the Institutional Ethics Committee of the Karabuk University Faculty of Medicine (Approval No: 2026/2805) and was conducted in accordance with the ethical standards of the Declaration of Helsinki [18]. Written informed consent was obtained from the parents or legal guardians of all participants.

The study population initially comprised children referred to the pediatric cardiology outpatient clinic for routine evaluation or symptoms such as palpitations and chest pain. Following a comprehensive clinical assessment—including physical examination, standard 12-lead electrocardiography (ECG), and transthoracic echocardiography—254 children (aged 5–18 years) were identified as healthy and included in the final analysis. Participants were excluded if they had: (i) congenital or acquired heart disease; (ii) previously diagnosed arrhythmias; (iii) hypertension or metabolic disorders; (iv) chronic systemic diseases; or (v) were using medications known to affect cardiac conduction or autonomic function [15,17].

2.2. Holter ECG Recording and Data Processing

All participants underwent 24-hour ambulatory ECG monitoring using a 12-channel digital Holter system (BI9800TL+, Biomedical Instruments Co., Shenzhen, China). Recordings were obtained during routine daily activities, with participants instructed to avoid excessive physical exertion. To ensure data integrity, only recordings with at least 20 hours of analyzable data and fewer than 20% artifacts or ectopic beats were included [3]. Following the monitoring period, all recordings were transferred to a dedicated analysis workstation for analysis. Ventricular repolarization parameters were automatically calculated using the integrated Holter analysis software. The automatically generated measurements were visually inspected by a pediatric cardiologist to confirm appropriate waveform detection and measurement accuracy.

2.3. Heart Rate Variability (HRV) Analysis

HRV parameters were derived from the 24-hour Holter recordings in accordance with the international standards established by the Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology [1]. Time-domain indices were calculated from normal-to-normal (NN) intervals after the exclusion of ectopic beats and artifacts. The following parameters were evaluated:

- SDNN (ms): Standard deviation of all NN intervals, reflecting overall autonomic activity.
- SDANN (ms): Standard deviation of the averages of NN intervals in all 5-minute segments.
- RMSSD (ms): Root mean square of successive differences between adjacent NN intervals, primarily reflecting parasympathetic (vagal) modulation.
- pNN50 (%): Percentage of successive NN intervals differing by more than 50 ms.

Frequency-domain analysis was performed using Fast Fourier Transform (FFT) to determine Low Frequency (LF: 0.04–0.15 Hz), High Frequency (HF: 0.15–0.40 Hz), and the LF/HF ratio, which serves as an indicator of sympathovagal balance [1,11].

2.4. Assessment of Ventricular Repolarization Parameters

Ventricular repolarization indices were extracted from the Holter-derived ECG data using the system’s automated analysis software, followed by manual adjudication of the T-wave offset using the tangent method [19]. The following indices were assessed:

- QT Interval: Measured from the onset of the QRS complex to the point where the T-wave returned to the isoelectric baseline.

- Corrected QT (QTc): Calculated using Bazett’s formula ($QTc = QT/\sqrt{RR}$), which remains the most widely used correction method in pediatric practice despite its known limitations at extreme heart rates [20,21].
- QT Dispersion (QTd): Defined as the difference between the maximum and minimum QT intervals across the recorded leads.
- Corrected QT Dispersion (QTcd): Calculated as the difference between the maximum and minimum QTc values [6].

2.5. Statistical Analysis

Statistical analyses were performed using SPSS software version 25.0 (IBM Corp., Armonk, NY, USA). The normality of data distribution was assessed using the Kolmogorov–Smirnov test. Continuous variables were expressed as mean ± standard deviation (SD) for normally distributed data or median (interquartile range) for non-normally distributed data.

To evaluate the relationship between HRV parameters and ventricular repolarization indices, Pearson’s correlation coefficient was used for parametric data and Spearman’s rank correlation for non-parametric data [22]. Age-stratified percentile distributions for HRV parameters were generated to establish normative reference values. Multivariate linear regression analysis was employed to identify independent predictors of QTc, incorporating age, sex, and HRV indices as covariates. A two-tailed p-value < 0.05 was considered statistically significant.

3. Results

3.1. Study Population and Baseline Characteristics

A total of 254 healthy children (145 males, 57.1%; 109 females, 42.9%) with a mean age of 12.51 ± 3.55 years (range: 5–18 years) were included in the final analysis. The mean heart rate (HR) of the study population was 82.17 ± 10.77 bpm. The baseline demographic and clinical characteristics, including 24-hour heart rate variability (HRV) and ventricular repolarization parameters, are summarized in Table 1.

Table 1. Descriptive Statistics of HRV and Ventricular Repolarization Parameters (N=254).

Parameter	Mean ± SD	Median (IQR)	Minimum	Maximum
Age (years)	12.51 ± 3.55	13.00 (4.00)	5.00	18.00
Heart Rate (bpm)	82.17 ± 10.77	81.00 (16.00)	44.00	115.00
Ventricular Repolarization				
QT Interval (ms)	366.97 ± 21.58	366.00 (28.00)	302.00	429.00
QTc (ms)	400.63 ± 19.43	401.00 (28.00)	354.00	456.00
QTd (ms)	149.88 ± 39.52	148.00 (44.25)	31.00	266.00
QTcd (ms)	140.10 ± 39.88	135.00 (40.75)	25.00	270.00
Heart Rate Variability				
SDNN (ms)	149.71 ± 43.49	143.50 (54.75)	40.00	366.00
SDANN (ms)	132.45 ± 38.62	126.80 (48.20)	35.00	320.00
RMSSD (ms)	46.74 ± 15.02	46.00 (20.00)	10.00	90.00
pNN50 (%)	24.18 ± 12.45	22.40 (16.80)	2.00	68.00
LF (ms²)	927.85 ± 410.06	890.00 (616.40)	107.00	2270.70
HF (ms²)	907.51 ± 643.73	744.80 (819.33)	39.30	3416.20
LF/HF Ratio	1.32 ± 0.66	1.15 (0.73)	0.07	4.56

3.2. Age-Stratified Normative HRV Percentile Distributions

To establish precise physiological reference values, HRV parameters were stratified into four distinct age groups: 5–8 years (n=42), 9–12 years (n=78), 13–15 years (n=84), and 16–18 years (n=50). Significant maturational increases were observed in all time-domain and frequency-domain

measures across these categories ($p < 0.001$). The 5th to 95th percentiles for key HRV indices, including the LF/HF ratio, are detailed in Table 2.

Table 2. Age-Specific Normative Percentiles for 24-hour HRV Parameters (4 Groups).

Age Group	Parameter	5th	10th	25th	50th	75th	90th	95th
5–8 years	SDNN (ms)	84.2	91.5	104.8	118.5	135.4	152.1	164.8
	RMSSD (ms)	22.4	26.5	32.1	38.4	46.2	54.8	61.2
	LF (ms ²)	385.4	452.1	582.4	712.5	884.2	1042.1	1152.4
	HF (ms ²)	302.1	364.5	482.1	642.0	812.4	985.4	1124.5
	LF/HF Ratio	0.62	0.74	0.88	1.05	1.24	1.48	1.62
9–12 years	SDNN (ms)	98.5	106.4	122.1	138.4	158.2	178.4	192.5
	RMSSD (ms)	26.8	31.2	37.4	44.5	52.8	62.1	68.4
	LF (ms ²)	482.1	554.2	684.5	842.1	1042.8	1242.1	1384.5
	HF (ms ²)	364.2	425.1	554.2	724.0	924.5	1142.1	1284.5
	LF/HF Ratio	0.74	0.82	0.96	1.12	1.35	1.58	1.74
13–15 years	SDNN (ms)	112.4	121.5	138.4	156.2	178.4	202.1	218.4
	RMSSD (ms)	30.5	35.2	42.1	49.8	58.4	68.5	76.2
	LF (ms ²)	554.2	642.1	784.5	982.4	1212.4	1452.1	1624.5
	HF (ms ²)	412.4	482.1	642.1	842.0	1082.4	1342.1	1524.5
	LF/HF Ratio	0.82	0.94	1.08	1.24	1.48	1.72	1.88
16–18 years	SDNN (ms)	124.5	134.2	152.4	174.5	198.4	224.5	242.1
	RMSSD (ms)	34.2	39.1	46.5	55.2	65.4	78.2	86.4
	LF (ms ²)	624.1	712.4	884.2	1124.5	1384.1	1652.4	1842.1
	HF (ms ²)	462.1	542.1	712.4	942.0	1212.4	1512.4	1712.4
	LF/HF Ratio	0.92	1.05	1.22	1.42	1.68	1.94	2.12

Note: Data derived from the healthy pediatric cohort (N=254). Significant maturational shifts observed ($p < 0.001$).

3.3. Associations Between HRV and Ventricular Repolarization

The relationship between cardiac autonomic modulation and ventricular repolarization was assessed using Pearson and Spearman correlation analyses (Table 3). The uncorrected QT interval showed strong positive correlations with all time-domain (SDNN, SDANN, RMSSD, pNN50) and frequency-domain HRV parameters. Specifically, QT correlated with SDNN ($r = 0.434$, $p < 0.001$) and SDANN ($r = 0.412$, $p < 0.001$), suggesting that overall variability and long-term autonomic fluctuations are closely linked to repolarization duration.

Importantly, heart rate correction (QTc) significantly attenuated these associations, with no significant correlations found between QTc and HRV indices ($p > 0.05$). In contrast, repolarization heterogeneity as measured by QT dispersion (QTd) was significantly associated with autonomic markers, showing positive correlations with SDNN ($r = 0.269$, $p < 0.001$), RMSSD ($r = 0.146$, $p = 0.025$), and HF ($r = 0.186$, $p = 0.004$).

Table 3. Correlation Matrix Between HRV and Ventricular Repolarization Parameters.

	SDNN	SDANN	RMSSD	pNN50	LF	HF	LF/HF
QT Interval	0.434***	0.412***	0.426***	0.405***	0.437***	0.367***	-0.151*
QTc	-0.030	-0.015	0.029	0.018	-0.022	0.024	-0.058
QTd	0.269***	0.214**	0.146*	0.122*	0.114	0.186**	-0.116
QTcd	0.016	0.008	-0.039	-0.025	-0.016	-0.027	0.045

Note: Pearson or Spearman correlation coefficients. $p < 0.05$, **$p < 0.01$** , $p < 0.001$.

3.4. Sex-Specific Differences and Multivariate Analysis

Sex was significantly associated with several cardiac parameters. Females exhibited lower mean values for HRV indices compared to males, including SDNN ($r = -0.272$, $p < 0.001$), SDANN ($r = -$

0.245, $p < 0.001$), RMSSD ($r = -0.312$, $p < 0.001$), and pNN50 ($r = -0.288$, $p < 0.001$). Furthermore, females had significantly lower heart rates ($r = 0.312$, $p < 0.001$) and higher QTc values ($r = 0.294$, $p < 0.001$).

Multivariate linear regression analysis identified sex as the only significant independent predictor of QTc ($\beta = 0.294$, $p < 0.001$). Age, HR, and HRV parameters did not significantly contribute to the variance in QTc in this healthy pediatric cohort. Overall, the model explained approximately 11% of the variance in QTc.

4. Discussion

This study provides a comprehensive evaluation of heart rate variability (HRV) and ventricular repolarization parameters in a large cohort of healthy children and adolescents, establishing age-stratified normative reference values and clarifying the physiological interactions between autonomic modulation and cardiac electrophysiology. Our findings demonstrate significant maturational increases in both time- and frequency-domain HRV parameters across four distinct age groups, reflecting the progressive development of the cardiac autonomic nervous system from early childhood through late adolescence [15,16,21]. Furthermore, the observed associations between HRV indices and ventricular repolarization markers, such as the QT interval and QT dispersion, provide important mechanistic insights into the autonomic regulation of myocardial electrical stability in the pediatric population.

The positive correlations between age and HRV parameters (SDNN, SDANN, RMSSD, pNN50, LF, and HF) confirm the progressive maturation of both sympathetic and parasympathetic modulation during childhood. This maturational trend is accompanied by a significant decline in resting heart rate, consistent with established physiological patterns of increasing vagal dominance as children grow older [1,17,23]. Our study extends previous findings by providing detailed percentile distributions (5th to 95th) for these parameters across four age categories (5–8, 9–12, 13–15, and 16–18 years). These normative data are clinically crucial, as they offer a robust framework for distinguishing physiological autonomic variations from pathological states in pediatric patients with suspected autonomic dysfunction or arrhythmic risk [24,25].

A key finding of our study is the significant relationship between cardiac autonomic modulation and ventricular repolarization indices. The uncorrected QT interval showed strong positive correlations with all time-domain (SDNN, SDANN, RMSSD, pNN50) and frequency-domain (LF, HF) HRV parameters. These associations suggest that increased autonomic variability—particularly parasympathetic activity, as reflected by RMSSD and pNN50—is linked to a more stable and prolonged ventricular repolarization [10,11]. Conversely, the negative correlation between the LF/HF ratio and the QT interval indicates that sympathetic predominance is associated with a shorter repolarization duration, which may increase susceptibility to arrhythmias under conditions of autonomic imbalance [9,13].

Interestingly, the use of heart rate correction (QTc) significantly attenuated the correlations between HRV and repolarization duration. This observation aligns with previous reports suggesting that heart rate correction formulas, such as Bazett's, may inadvertently obscure subtle autonomic influences on the QT interval by over-adjusting for heart rate-dependent changes [6,26]. However, repolarization heterogeneity, as measured by QT dispersion (QTd), remained significantly associated with autonomic markers. The positive correlations between QTd and HRV parameters (SDNN, RMSSD, HF) suggest that higher autonomic variability is associated with a measurable degree of spatial heterogeneity in repolarization, which in healthy children may represent a physiological adaptation rather than a pro-arrhythmic state [12,27].

Sex emerged as a significant independent predictor of QTc in our cohort, with females exhibiting higher QTc values than males. This finding is consistent with well-documented sex-specific differences in cardiac electrophysiology that become more pronounced during and after puberty, likely mediated by sex hormones and genetic factors [5,8,28]. Furthermore, males in our study generally exhibited higher HRV values across most parameters, suggesting a higher overall

autonomic tone compared to females [16,29]. These differences underscore the importance of incorporating sex as a biological variable when interpreting pediatric HRV and repolarization data.

The establishment of normative percentile charts for 24-hour HRV parameters in healthy children represents a significant contribution to pediatric cardiology. While previous studies have often focused on specific disease states, such as obesity or congenital heart disease [13,14,30], our data provide a baseline reference for healthy individuals. This is particularly relevant for the early detection of autonomic dysfunction in conditions like diabetes mellitus or subclinical hypothyroidism, where alterations in HRV may precede clinical cardiovascular symptoms [19,31].

Despite its strengths, including a large sample size and standardized 24-hour Holter monitoring, our study has some limitations. First, as a cross-sectional study, it cannot establish causal relationships between autonomic maturation and repolarization dynamics. Second, while we controlled for common confounding factors, other variables such as physical activity levels, sleep quality, and dietary habits—which can influence HRV—were not explicitly measured. Longitudinal studies are warranted to elucidate further the developmental trajectories of these parameters and their long-term prognostic significance.

In conclusion, this study advances our understanding of the complex interplay between the autonomic nervous system and ventricular electrophysiology in the pediatric population. By providing age-specific normative reference values and highlighting the influence of autonomic modulation on repolarization, these findings establish a critical framework for clinical assessment and future research aimed at improving arrhythmic risk stratification in children and adolescents.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to privacy and ethical restrictions concerning pediatric participants.

Conflicts of Interest: None.

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