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ORIGINAL ARTICLE

Heart rate variability in diabetes; evidence of autonomic dysfunction across age groups

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ABSTRACT

Background: Heart rate variability (HRV) serves as a non-invasive marker of autonomic nervous system function. In individuals with diabetes mellitus, cardiac autonomic neuropathy is a recognized complication that may manifest as reduced HRV and increased heart rate (HR). This study aimed to assess differences in HR and HRV between diabetic and non-diabetic individuals and explore age-related variations.

Methods: A total of 64 subjects were included, comprising 33 individuals with diabetes and 31 non-diabetic controls. Short-term ECG recordings were analyzed to calculate average HR and HRV. Participants were further divided into ten age groups spanning 26–85 years, and subgroup analyses were performed to examine trends across age brackets.

Results: Diabetic participants had a higher average heart rate (86 bpm) compared to non-diabetics (77 bpm), along with significantly lower HRV (0.0185 vs. 0.0333). Age-stratified analyses revealed a consistent pattern of higher HR and lower HRV among diabetic individuals across most age groups. In the 41–45 age group, diabetics exhibited an average HR of 89 bpm and HRV of 0.0179, whereas non-diabetics had 77 bpm and 0.0358, respectively. in the 56–60 age group, diabetic participants had an average heart rate of 85 bpm and an HRV of 0.0136, whereas non-diabetic participants had a lower average heart rate of 73 bpm and a higher HRV of 0.0262.

Conclusion: This study reveals that diabetes is associated with reduced autonomic flexibility, as reflected by lower HRV and elevated HR. These alterations suggest early cardiac autonomic dysfunction, which may increase cardiovascular risk. Routine HRV assessment could enhance clinical monitoring and risk stratification in diabetic patients, particularly when combined with emerging digital health technologies.

Keywords: heart rate variability; diabetes mellitus; autonomic dysfunction; cardiovascular risk.

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Introduction

Heart rate variability (HRV) serves as a vital indicator of autonomic nervous system function, offering insight into the dynamic interplay between sympathetic and parasympathetic regulation of the cardiovascular system (1). HRV reflects the body's ability to respond adaptively to stress, physical activity, and internal physiological changes. In healthy individuals, high HRV signifies greater cardiovascular resilience and

flexibility, while reduced HRV has been associated with various pathological conditions, including cardiac arrhythmias, hypertension, and metabolic disorders (2).

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Among these conditions, diabetes mellitus has been particularly linked to impaired autonomic regulation (3). Chronic hyperglycemia and insulin resistance contribute to autonomic neuropathy, which manifests in diminished vagal tone and sympathetic dominance resulting in lower HRV (3). This autonomic imbalance increases the risk of adverse cardiovascular events, even in the absence of overt heart disease. Literature has reported lower HRV in individuals with diabetes, positioning HRV as a potential non-invasive marker for early detection of diabetic complications (4).

Despite the global attention diabetes receives, there remains a need for local studies that explore its physiological consequences in specific populations (5). In Pakistan, where the prevalence of diabetes is steadily rising, there is limited data on the cardiovascular autonomic function of diabetic patients compared to non-diabetic individuals. Moreover, factors such as lifestyle, genetics, and healthcare access may influence the progression of autonomic dysfunction in this population, emphasizing the importance of context-specific research (6).

ECG-based HRV assessment has emerged as a reliable, low-cost, and accessible method to evaluate autonomic function (7). Short-duration ECG recordings, when conducted under standardized resting conditions, can yield valuable metrics such as the standard deviation of RR intervals, providing a window into an individual's autonomic health (8). With advancements in signal processing techniques and analytical software such as MATLAB, it is now possible to extract HRV parameters with high precision, even in clinical settings (9).

The objective of this study was to compare heart rate variability between diabetic and non-diabetic individuals using short-term ECG recordings under controlled conditions. By examining differences in HRV metrics and exploring potential correlations with age and diabetes duration, this study aimed to shed light on the extent of autonomic impairment in diabetic patients. Ultimately, the findings may support the utility of HRV as a screening tool for cardiovascular risk stratification in routine diabetic care.

Methods

This study utilized a comparative cross-sectional design to evaluate HRV in diabetic and non-diabetic individuals. The research was conducted at Alkhidmat Raazi Hospital, Rawalpindi, from September 2023 to February 2024. Participants were recruited from outpatient clinics to ensure a diverse and representative sample. A total of 64 participants were recruited using purposive sampling, consisting of 33 diabetic patients and 31 non-diabetic controls. The inclusion and exclusion criteria were established to minimize confounding factors affecting heart rate dynamics.

The inclusion criteria for this study encompassed individuals aged between 25 and 85 years. Participants in the diabetic group were required to have a confirmed diagnosis of diabetes based on the American Diabetes Association (ADA) 2022 guidelines, which include a fasting glucose level greater

than 126 mg/dL or an HbA1c level exceeding 6.5%. Non-diabetic individuals were included only if they had no history of metabolic or cardiovascular disease. Participants were excluded if they had a history of cardiovascular conditions such as ischemic heart disease, arrhythmias, or heart failure. Additionally, individuals using beta-blockers or other medications known to affect autonomic function were not considered for inclusion. Other exclusion criteria included the presence of conditions that could alter HRV, such as neurological disorders, thyroid dysfunction, or chronic kidney disease.

The Institutional Review Board of Alkhidmat Raazi Hospital approved this study via letter no IRB/A/06/23 dated 27th, March, 2023. Written informed consent was obtained from all participants before data collection, ensuring compliance with the Declaration of Helsinki. Participants were informed about the study objectives, risks, and voluntary nature of participation, with the option to withdraw at any stage.

A two-minute electrocardiogram was recorded for each participant under standardized conditions to ensure reproducibility and minimize external influences on HRV measurements. A 12-lead ECG device was used, with a sampling rate of 250 Hz to facilitate accurate detection of R-peaks. Electrodes were placed in the standard limb lead configuration, with Lead II preferred for optimal R-wave visualization. Participants were instructed to maintain a supine resting position in a quiet, temperature-controlled room (25°C), avoid caffeine, smoking, or vigorous physical activity for six hours prior to recording, and to breathe normally without speaking or moving during ECG acquisition.

Accurate heart rate computation requires precise R-peak detection in the ECG signal. To achieve this, a custom algorithm was developed for automated R-wave identification and HRV computation. The entire signal processing and HRV analysis were performed using MATLAB, where custom scripts were developed to automate peak detection, filter optimization, and statistical computation.

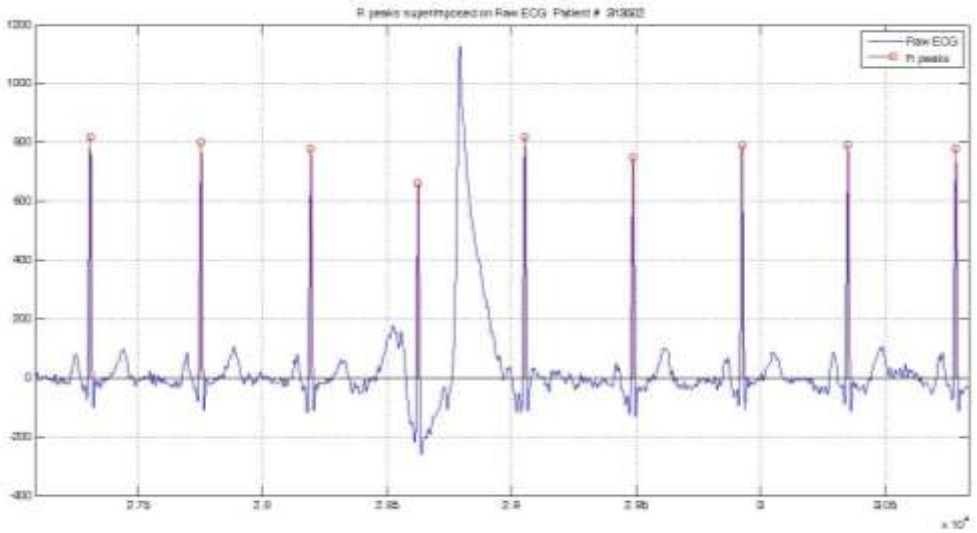

Figure 1. R-Peaks Superimposed on Raw ECG Signal

The raw ECG signals were preprocessed using the Butterworth filtering technique to remove unwanted noise and improve signal quality. This involved eliminating baseline drift, which results from low-frequency fluctuations caused by respiration and electrode movement. Additionally, high-frequency artifacts originating from muscle noise and power-line interference were filtered out to ensure a cleaner signal. To further refine the data, adaptive thresholding was applied to detect and exclude outlier observations and ectopic beats that could distort HRV calculations.

The detection of R-peaks followed a structured multi-step approach. Initially, an Iteratively Re-Weighted Least Squares (IRWLS) method was employed to estimate the maximum likelihood parameters of a first-order linear model. These parameters acted as reference anchors, with inverted weights computed to highlight potential R-wave occurrences. In the post-processing step, detected peaks were validated using confidence interval analysis, ensuring that only physiologically plausible peaks were retained. To maintain accuracy, peaks were accepted only if they satisfied a physiological RR interval range of 600–1200 ms, thereby eliminating false positives and ensuring the reliability of the data.

Following the detection of R-peaks, heart rate was computed as the reciprocal of the time interval between successive R-peaks. HRV was assessed using the standard deviation of RR intervals over the two-minute recording period.

To assess the impact of age and diabetes duration on HRV, participants were categorized into age groups each spanning five-year intervals. Diabetic participants were further stratified based on the known duration of their condition to explore potential trends in autonomic function decline over time. Group-wise comparisons of HR and HRV were conducted using appropriate statistical tests, with significance set at $p < 0.05$. MATLAB was used for statistical computations, including the calculation of mean HR and HRV values.

Results

Heart rate variability analysis was conducted on 64 subjects, including 33 individuals with diabetes and 31 without. The study included 64 participants ranging in age from 26 to 85 years, with a mean age of 49.5 ± 13.6 years. The diabetic group had a mean age of 50.1 ± 13.8 years, closely matching that of the non-diabetic group, which was 48.9 ± 13.4 years. An independent samples t-test confirmed no statistically significant age difference between the two groups ($p = 0.68$).

Regarding gender distribution, females comprised 56% (N=36) of the overall study population, while males accounted for 44% (N=28). Within diabetic participants, females represented 59% (N=20), compared to 41% males (N=14). Similarly, among non-diabetic subjects, the proportion was 55% females (N=16) and 45% males (N=14). Chi-square testing found no significant differences in gender distribution between the diabetic and non-diabetic groups ($\chi^2=0.13$, $p=0.72$).

The overall average heart rate was higher in diabetic participants (86 bpm compared to non-diabetic participants (77 bpm). In contrast, the average HRV was lower in diabetics (0.0185) than in non-diabetics (0.0333), indicating reduced autonomic flexibility among the diabetic group.

Below and above 50 years, weighted average HRV was lower in diabetics across both groups (0.0214 and 0.0158, respectively) compared to non-diabetics (0.0354 and 0.0300, respectively). Further age-based

subgroup analysis, organized in five-year intervals, revealed consistent patterns. In most age brackets, diabetic individuals exhibited higher average heart rates and significantly lower HRV compared to their non-diabetic counterparts. Notably, in the 41–45 age group, diabetics had an average heart rate of 89 bpm and HRV of 0.0179, whereas non-diabetics recorded an average heart rate of 77 bpm and HRV of 0.0358 ($p = 0.006$). Similar statistically significant differences in HRV were observed in the 26–30 ($p = 0.017$), 36–40 ($p = 0.043$), 51–55 ($p = 0.022$), 56–60 ($p = 0.038$), and 61–65 ($p = 0.031$) age groups. In age categories with limited sample sizes, statistical comparison was not feasible. (Table 1)

Table 1. Age-wise comparison of average heart rate and heart rate variability between diabetic and non-diabetic subjects

Group Number	Age Group	Class Type	Number of subjects	Average Heart Rate	Average Heart Rate Variability	
1	26-30	Diabetic	2	97	.0216	0.017
		Non-Diabetic	6	83	.0367	
2	31-35	Diabetic	2	82	.0221	NaN
		Non-Diabetic	1	70	.0412	
3	36-40	Diabetic	3	84	.0244	0.043
		Non-Diabetic	5	76	.0364	
4	41-45	Diabetic	4	89	.0179	0.006
		Non-Diabetic	6	77	.0358	
5	46-50	Diabetic	6	84	.0218	NaN
		Non-Diabetic	1	75	.0140	
6	51-55	Diabetic	4	94	.0128	0.022
		Non-Diabetic	2	82	.0192	
7	56-60	Diabetic	6	85	.0136	0.038
		Non-Diabetic	6	73	.0262	
8	61-65	Diabetic	3	73	.0277	0.031
		Non-Diabetic	2	80	.0342	
9	66-70	Diabetic	2	98	.0107	NaN
		Non-Diabetic	1	57	.0702	
10	81-85	Diabetic	1	70	.0155	NaN
		Non-Diabetic	1	72	.0252	

A few anomalies were observed in subgroups with very small sample sizes (e.g., groups containing only one subject), such as the non-diabetic subject in the 66–70 age group who had an unusually low heart rate (57 bpm) and a high HRV (0.0702). These outliers likely reflect the limitations of minimal data in those specific groups rather than representative physiological differences.

To assess statistical differences between diabetic and non-diabetic participants, independent samples t-tests were conducted. These analyses revealed that average heart rate was significantly higher in diabetic individuals ($M = 86$ bpm, $SD = 7.2$) compared to non-diabetics ($M = 76.7$ bpm, $SD = 7.5$), $t(62) = 5.51$, $p < .001$. Similarly, heart rate variability (HRV) was significantly lower

among diabetics (M = 0.0186, SD = 0.0097) than in non-diabetics (M = 0.0333, SD = 0.0092), t (62) = -6.00, p < .001. Table 2. These findings indicate an overall statistically significant difference in both heart rate and HRV between diabetic and non-diabetic subjects.

Table 2: Overall comparison of heart rate and HRV between diabetic and non-diabetic subjects

Class Type	Number of Subjects	Average Heart Rate (bpm), Mean ± SD	Average HRV, Mean ± SD	t-value (HR)	p-value (HR)	t-value (HRV)	p-value (HRV)
Diabetic	37	86 ± 7.2	0.0186 ± 0.0097	5.51	<0.001	-6.00	<0.001
Non-Diabetic	27	76.7 ± 7.5	0.0333 ± 0.0092				

Discussion

This study examined heart rate variability (HRV) and heart rate (HR) differences between diabetic and non-diabetic individuals, revealing significant alterations in autonomic function associated with diabetes. Diabetic participants exhibited a higher average HR (86 bpm) compared to non-diabetic controls (77 bpm), alongside a markedly reduced HRV (0.0185 vs. 0.0333). These findings demonstrate the presence of cardiac autonomic dysfunction in individuals with diabetes, consistent with previous research indicating diminished autonomic flexibility and impaired autonomic regulation in this population (10, 11).

A systematic review by Benichou et al. (2018) highlighted that both sympathetic and parasympathetic activities are diminished in type 2 diabetes mellitus (T2DM), leading to decreased HRV across various parameters (12). This autonomic imbalance is attributed to the deleterious effects of chronic hyperglycemia on the autonomic nervous system, resulting in CAN (13). The diminished HRV observed in our study reflects this pathophysiological mechanism, emphasizing the impact of diabetes on cardiac autonomic control. Age-stratified analyses further revealed that diabetic individuals consistently exhibited higher heart rates and lower HRV across most age groups, with these differences reaching statistical significance in several strata. For instance, in the 41–45 age bracket, diabetics had an average HR of 89 bpm and HRV of 0.0179, whereas non-diabetics recorded 77 bpm and 0.0358, respectively (p = 0.006). Statistically significant differences in HRV were also observed in the 26–30 (p = 0.017), 36–40 (p = 0.043), 51–55 (p = 0.022), 56–60 (p = 0.038), and 61–65 (p = 0.031) age groups. These findings suggest that diabetes exacerbates age-related declines in autonomic function (14). While aging naturally leads to a reduction in HRV, the presence of diabetes appears to accelerate this decline, as supported by studies indicating that diabetic patients experience a more pronounced decrease in HRV with advancing age (15,16). The elevated HR observed in diabetic participants may reflect increased sympathetic activity or reduced parasympathetic tone, both hallmarks of autonomic dysfunction (17). Elevated resting HR has been associated with higher cardiovascular risk and mortality in diabetic populations (18). The combination of increased HR and reduced HRV in our diabetic cohort underscores the heightened

cardiovascular risk associated with autonomic imbalance in diabetes.

Notably, our study identified anomalies in subgroups with minimal sample sizes, such as the 66–70 age group, where a non-diabetic individual exhibited an unusually low HR (57 bpm) and high HRV (0.0702). These outliers likely reflect individual variability rather than representative physiological differences, highlighting the importance of adequate sample sizes for reliable subgroup analyses. The clinical implications of our findings are significant. Reduced HRV is said to be associated with increased risk of arrhythmias, silent myocardial ischemia, and sudden cardiac death in diabetic patients (19). Early detection of autonomic dysfunction through HRV assessment can facilitate timely interventions aimed at mitigating cardiovascular risk. Incorporating HRV analysis into routine clinical evaluations for diabetic patients may enhance risk stratification and guide therapeutic strategies (20).

Furthermore, our study underscores the utility of short-term ECG recordings for HRV assessment. Despite the brevity of the recordings, significant differences in HRV between diabetic and non-diabetic individuals were detectable, suggesting that short-term HRV analysis can serve as a practical tool for evaluating autonomic function in clinical settings. In light of rapid advancements in digital health technologies, there is growing potential to leverage artificial intelligence (AI) and big data analytics to enhance the diagnostic and predictive utility of heart rate variability (21). Wearable devices and mobile health applications now enable continuous HRV monitoring outside clinical settings, generating large-scale, real-time datasets (22). These datasets can be utilized to train machine learning models capable of identifying subtle patterns and early warning signs of cardiovascular dysfunction, particularly in high-risk populations such as diabetics (23). Recent studies have demonstrated the effectiveness of AI-based in predicting major adverse cardiac events, including arrhythmias and myocardial infarction (24). However, the reliability of such AI models depends heavily on the quality and diversity of input data (25). Therefore, there is a pressing need for multicentric collaborations and standardization of HRV measurement protocols to ensure the development of new and generalizable predictive algorithms.

Conclusion

This study underscores a clear relationship between diabetes and impaired cardiac autonomic function, as evidenced by higher heart rates and significantly reduced heart rate variability in diabetic individuals across most age groups. These findings highlight the potential of HRV as a non-invasive, early marker for cardiovascular risk in diabetic populations. The consistent trends observed in age-stratified analysis further suggest that diabetes may accelerate autonomic decline with aging. Integrating HRV assessment into routine diabetic care could enhance early detection of cardiac autonomic neuropathy and guide timely interventions.

Recommendations

Future research with larger, more diverse cohorts and integration of advanced digital tools such as AI-driven HRV analysis may pave the way for improved risk stratification and personalized care in diabetes management.

Strength and limitations of study

A key strength lies in the structured age-wise subgroup analysis, which highlights consistent patterns across various age brackets. Additionally, the use of short-term ECG data demonstrates the practical applicability of HRV monitoring in clinical settings. However, the study also has limitations. The overall sample size is relatively small, and certain subgroups had very few participants, which may reduce the reliability of age-specific comparisons and increase the influence of outliers. These factors may applicability of the findings and highlight the need for larger, multicenter studies to validate the results.

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Conflict of interest: None

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All the authors agree to take responsibility for every facet of the work, making sure that any concerns about its integrity or veracity are thoroughly examined and addressed.