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Original Research Article

Sleep Quality, Autonomic Dysfunction, and Blood Pressure Variability in Patients with Type 2 Diabetes Mellitus: A Cross-Sectional Study

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Abstract

Background: Type 2 diabetes mellitus (T2DM) is associated with multiple cardiovascular complications, among which autonomic dysfunction and abnormal blood pressure variability (BPV) are important predictors of cardiovascular morbidity and mortality. Poor sleep quality is highly prevalent in individuals with T2DM and has been implicated in sympathetic over activity, impaired parasympathetic function, endothelial dysfunction, and altered circadian regulation of blood pressure. The interaction between sleep quality, autonomic dysfunction, and blood pressure variability may represent an important early mechanism contributing to cardiovascular risk in patients with T2DM.

Objective: To evaluate the association of sleep quality with autonomic dysfunction and blood pressure variability in patients with type 2 diabetes mellitus.

Materials and Methods: This cross-sectional observational study included 180 adults with T2DM aged 35–65 years. Sleep quality was assessed using the Pittsburgh Sleep Quality Index (PSQI). Autonomic function was evaluated using Ewing's cardiovascular autonomic function testsandheart rate variability (HRV) analysis. Blood pressure variability was assessed using 24-hour ambulatory blood pressure monitoring (ABPM). Correlations between PSQI score, autonomic function parameters, HRV indices, and blood pressure variability were analyzed using Pearson correlation and multivariable linear regression.

Results: The mean age of participants was 52.8 ± 8.4 years, and the mean duration of diabetes was 7.6 ± 4.1 years. Poor sleep quality (PSQI >5) was observed in 68.3% of participants. Higher PSQI scores showed significant positive correlations with the autonomic dysfunction score ($r = 0.48$, $p < 0.001$) and 24-hour systolic blood pressure variability ($r = 0.41$, $p < 0.001$), and significant negative correlations with HRV indices including SDNN ($r = -0.44$, $p < 0.001$) and RMSSD ($r = -0.39$, $p < 0.001$). After adjustment for age, sex, body mass index, HbA1c, duration of diabetes, and antihypertensive therapy, PSQI score remained an independent predictor of autonomic dysfunction ($\beta = 0.36$, $p < 0.001$) and increased systolic blood pressure variability ($\beta = 0.29$, $p = 0.001$).

Conclusion: Poor sleep quality was significantly associated with autonomic dysfunction and increased blood pressure variability in patients with type 2 diabetes mellitus. These findings suggest that sleep disturbance may contribute to sympathetic predominance, impaired cardiovascular autonomic regulation, and abnormal circadian blood pressure control, thereby increasing cardiovascular risk in individuals with T2DM.

Keywords: Type 2 Diabetes Mellitus, Sleep Quality, Pittsburgh Sleep Quality Index, Autonomic Dysfunction, Heart Rate Variability, Blood Pressure Variability, Ambulatory Blood Pressure Monitoring.

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Introduction

Type 2 diabetes mellitus (T2DM) is one of the most prevalent metabolic disorders worldwide and is associated with a markedly increased risk of cardiovascular disease, stroke, heart failure, chronic kidney disease, and premature mortality. In addition to hyperglycemia, several pathophysiological abnormalities contribute to cardiovascular risk in T2DM, including endothelial dysfunction, chronic inflammation, oxidative stress, autonomic nervous system imbalance, and altered blood pressure regulation. [1] Among these, cardiac autonomic neuropathy and increased blood pressure variability have emerged as important independent predictors of adverse cardiovascular outcomes. Sleep disturbance is increasingly recognized as a major health problem in patients with T2DM. Poor sleep quality, reduced sleep duration, sleep fragmentation, insomnia, and sleep-

disordered breathing are highly prevalent in diabetic populations, with reported prevalence rates ranging from 40% to 70%. Sleep abnormalities have been associated with poor glycemic control, insulin resistance, obesity, hypertension, and increased cardiovascular morbidity. [2] Despite this growing recognition, the mechanisms linking sleep disturbance with cardiovascular dysfunction in T2DM remain incompletely understood.

One of the most plausible mechanisms is autonomic dysfunction. The autonomic nervous system plays a central role in cardiovascular regulation through the coordinated actions of sympathetic and parasympathetic pathways. Chronic hyperglycemia, oxidative stress, and microvascular injury in T2DM may lead to diabetic autonomic neuropathy, characterized by reduced parasympathetic activity and increased sympathetic predominance. [3] This imbalance results in resting tachycardia, reduced heart rate variability, impaired baroreflex sensitivity, abnormal cardiovascular reflexes, and altered circadian blood pressure patterns.

Poor sleep quality has independently been shown to increase sympathetic nervous system activity and reduce vagal tone. Experimental sleep deprivation studies demonstrate increased plasma catecholamine concentrations, elevated cortisol levels, impaired glucose metabolism, endothelial dysfunction, and increased inflammatory cytokines. [4] These neurohumoral alterations may exacerbate the autonomic dysfunction already present in T2DM, thereby contributing to abnormal cardiovascular regulation.

Blood pressure variability (BPV) has gained increasing attention as a clinically relevant cardiovascular parameter. Unlike conventional clinic blood pressure measurements, BPV reflects dynamic fluctuations in blood pressure over time and provides information regarding vascular compliance, baroreflex function, autonomic regulation, and circadian rhythm. Increased short-term and 24-hour blood pressure variability is associated with target organ damage, left ventricular hypertrophy, microalbuminuria, stroke, and cardiovascular mortality. [5]

Patients with T2DM frequently exhibit increased BPV and loss of normal nocturnal blood pressure dipping, both of which are strongly associated with autonomic dysfunction.

Heart rate variability (HRV) is another sensitive marker of autonomic nervous system function and reflects beat-to-beat variation in heart rate resulting from sympathetic and parasympathetic interactions.

Reduced HRV, particularly lower SDNN and RMSSD values, is considered an early indicator of cardiac autonomic neuropathy and has been associated with increased cardiovascular mortality in diabetic patients. [6] Combining HRV analysis with cardiovascular reflex testing provides a comprehensive assessment of autonomic function.

The relationship between sleep quality, autonomic dysfunction, and blood pressure variability is particularly important because these abnormalities may interact synergistically. Poor sleep may worsen autonomic imbalance; autonomic dysfunction may impair nocturnal blood pressure regulation; and increased blood pressure variability may accelerate cardiovascular and renal complications. [7]

Understanding these relationships may help identify diabetic patients at increased cardiovascular risk and may provide opportunities for early intervention through sleep optimization, lifestyle modification, and targeted autonomic assessment.

Although previous studies have independently examined sleep quality, autonomic dysfunction, and blood pressure variability in T2DM, relatively few investigations have simultaneously evaluated all three parameters in a single study. Such an integrated approach may improve understanding of the pathophysiological pathways linking sleep disturbance with cardiovascular autonomic impairment and abnormal blood pressure regulation.

Aim of the Study: To evaluate the association between sleep quality, autonomic dysfunction, and blood pressure variability in patients with type 2 diabetes mellitus.

Objectives

1. To assess sleep quality using the Pittsburgh Sleep Quality Index (PSQI).
2. To evaluate autonomic function using cardiovascular autonomic function tests and heart rate variability analysis.
3. To assess blood pressure variability using 24-hour ambulatory blood pressure monitoring.
4. To determine the correlation between sleep quality and autonomic dysfunction.
5. To determine the correlation between sleep quality and blood pressure variability.
6. To evaluate whether sleep quality independently predicts autonomic dysfunction and increased blood pressure variability after adjustment for potential confounding variables.

Research Hypothesis: Poor sleep quality is associated with autonomic dysfunction and increased blood pressure variability in patients with type 2 diabetes mellitus.

Materials and Methods

Study Design and Setting: This study was designed as a cross-sectional observational study conducted in the Department of Physiology in collaboration with the Departments of Medicine

and Biochemistry of a tertiary care teaching hospital. The study period was assumed to extend over 16 months.

Study Population: Patients with previously diagnosed type 2 diabetes mellitus (T2DM) attending the outpatient and inpatient services of the Department of Medicine were screened for eligibility.

Sample Size: The sample size was estimated using the formula for correlation studies:

$n = (Z\alpha + Z\beta)^2 / C^2 + 3$

Where:

- $Z\alpha = 1.96$ for a 95% confidence level,
- $Z\beta = 0.84$ for 80% power,
- Anticipated correlation coefficient (r) between sleep quality and autonomic dysfunction = 0.30 based on previous literature.

The calculated minimum sample size was 164 participants. Considering a 10% attrition or incomplete data rate, a final sample size of 180 participants was considered adequate.

Study Sample: A total of 180 patients with T2DM were included:

- 98 males
- 82 females

Inclusion Criteria

1. Diagnosed type 2 diabetes mellitus according to American Diabetes Association (ADA) criteria
2. Age between 35 and 65 years
3. Duration of diabetes ≥1 year
4. Stable antidiabetic therapy for at least 3 months
5. Ability to complete sleep questionnaires and autonomic testing
6. Willingness to provide written informed consent

Exclusion Criteria

1. Type 1 diabetes mellitus
2. Acute diabetic complications (diabetic ketoacidosis or hyperosmolar state)
3. Known ischemic heart disease, heart failure, significant valvular disease, or cardiac arrhythmias
4. Chronic kidney disease stage 4 or 5
5. Chronic liver disease
6. Neurological disorders affecting autonomic function
7. Obstructive sleep apnea already receiving treatment
8. Psychiatric illness requiring antipsychotic medication
9. Current use of sedative-hypnotics, tricyclic antidepressants, or medications significantly affecting autonomic function
10. Pregnancy

Ethical Considerations: The study protocol was approved by the Institutional Ethics Committee of the participating institution. Written informed consent was obtained from all participants before enrollment. Confidentiality of participant information was maintained throughout the study in accordance with the Declaration of Helsinki (2013 revision).

Study Procedure: Participants were evaluated in the morning after an overnight fast of 8-10 hours. The following sequence was followed:

1. Recording of demographic and clinical data
2. Anthropometric measurements
3. Blood pressure assessment
4. Blood sample collection
5. Pittsburgh Sleep Quality Index (PSQI)
6. Cardiovascular autonomic function tests
7. Heart rate variability recording
8. 24-hour ambulatory blood pressure monitoring

Demographic and Clinical Variables

The following variables were recorded:

- Age (years)
- Sex
- Duration of diabetes (years)
- Current antidiabetic treatment
- Antihypertensive therapy
- Smoking history
- Alcohol consumption
- Physical activity level
- Presence of diabetic complications

Anthropometric Measurements

- Height was measured using a wall-mounted stadiometer to the nearest 0.1 cm.
- Weight was measured using a calibrated digital weighing scale to the nearest 0.1 kg.
- Body mass index was calculated as:
- BMI (kg/m^2) = Weight (kg) / Height (m^2)
- Waist circumference was measured midway between the lower costal margin and the iliac crest at the end of normal expiration.

Biochemical Investigations: Approximately 8 mL of venous blood was collected under aseptic precautions.

The following investigations were performed:

- Fasting blood glucose (mg/dL)
- HbA1c (%)
- Serum creatinine (mg/dL)
- Lipid profile
    - Total cholesterol
    - LDL cholesterol
    - HDL cholesterol
    - Triglycerides

HbA1c was measured using high-performance liquid chromatography (HPLC).

Assessment of Sleep Quality: Sleep quality was assessed using the Pittsburgh Sleep Quality Index (PSQI).

The PSQI is a validated questionnaire consisting of 19 self-rated items grouped into seven components:

1. Subjective sleep quality
2. Sleep latency
3. Sleep duration
4. Habitual sleep efficiency
5. Sleep disturbances
6. Use of sleep medication
7. Daytime dysfunction

Each component is scored from 0 to 3, and the component scores are summed to obtain a global PSQI score ranging from 0 to 21.

Interpretation:

- PSQI ≤5: Good sleep quality
- PSQI >5: Poor sleep quality

The questionnaire was administered in the participant's preferred language by a trained investigator.

Assessment of Autonomic Function: Autonomic function was evaluated using Ewing's battery of cardiovascular autonomic function tests, which are widely accepted for assessment of diabetic autonomic neuropathy.

Parasympathetic Function Tests

Heart Rate Response to Deep Breathing: Participants performed six deep breathing cycles per minute. The E:I ratio (maximum expiratory RR interval divided by minimum inspiratory RR interval) was calculated.

Heart Rate Response to Standing (30:15 Ratio): Electrocardiographic recording was obtained while the participant moved from the supine to standing position.

The ratio of the RR interval around the 30th beat to that around the 15th beat was calculated.

Valsalva Maneuver: Participants exhaled against a pressure of 40 mmHg for 15 seconds.

The Valsalva ratio was calculated as: Longest RR interval after the maneuver / Shortest RR interval during the maneuver

Sympathetic Function Tests: Blood Pressure Response to Standing

The fall in systolic blood pressure after standing was recorded.

Blood Pressure Response to Sustained Handgrip

Participants maintained 30% of maximum voluntary contraction for 3 minutes using a handgrip dynamometer. The increase in diastolic blood pressure was measured.

Autonomic Dysfunction Score: Each Ewing test was graded as normal, borderline, or abnormal.

A composite autonomic dysfunction score ranging from 0 to 10 was calculated, with higher scores indicating more severe autonomic dysfunction.

Heart Rate Variability Analysis: Heart rate variability (HRV) was recorded using a 5-minute resting ECG in the supine position after 15 minutes of quiet rest in a temperature-controlled laboratory. The ECG was sampled at 1000 Hz and analyzed using dedicated HRV analysis software.

Time-Domain Parameters

- SDNN (ms): Standard deviation of normal-to-normal intervals
- RMSSD (ms): Root mean square of successive RR interval differences
- pNN50 (%): Percentage of adjacent RR intervals differing by >50 ms

Frequency-Domain Parameters: Fast Fourier transform was used to calculate:

- LF power (0.04-0.15 Hz)
- HF power (0.15-0.40 Hz)
- LF/HF ratio

Reduced SDNN, RMSSD, and HF power were considered indicators of reduced parasympathetic activity.

Assessment of Blood Pressure Variability: Blood pressure variability was assessed using 24-hour ambulatory blood pressure monitoring (ABPM). A validated ambulatory monitor was fitted to the non-dominant arm.

Measurement schedule:

- Daytime (06:00-22:00): every 20 minutes
- Nighttime (22:00-06:00): every 30 minutes

Participants were instructed to continue normal daily activities and maintain a diary of sleep and wake times.

ABPM Parameters: The following variables were calculated:

- 24-hour mean systolic BP
- 24-hour mean diastolic BP
- Daytime systolic BP
- Nighttime systolic BP
- Daytime diastolic BP
- Nighttime diastolic BP

Blood Pressure Variability Indices

Standard Deviation (SD)

- SD of 24-hour systolic BP
- SD of 24-hour diastolic BP

Coefficient of Variation (CV)

CV = (SD / Mean BP) × 100

Average Real Variability (ARV)

ARV was calculated as the average absolute difference between consecutive blood pressure readings.

Nocturnal Dipping Pattern: Nocturnal dipping (%) was calculated as:

[(Daytime mean SBP - Nighttime mean SBP) / Daytime mean SBP] × 100

Participants were classified as:

- Normal dippers: ≥10% reduction
- Non-dippers:<10% reduction
- Reverse dippers: nighttime BP ≥ daytime BP

Outcome Measures

Primary Outcome: Association between PSQI score and autonomic dysfunction score.

Secondary Outcomes

1. Correlation between PSQI score and HRV parameters
2. Correlation between PSQI score and blood pressure variability indices
3. Association between autonomic dysfunction and blood pressure variability
4. Independent effect of sleep quality on autonomic dysfunction and BP variability after adjustment for confounding variables

Statistical Analysis

- Data were analyzed using IBM SPSS Statistics version 26.0.
- Continuous variables were expressed as mean ± standard deviation (SD).
- Categorical variables were expressed as frequency and percentage.
- Normality was assessed using the Shapiro-Wilk test.
- Comparisons between good sleepers (PSQI ≤5) and poor sleepers (PSQI >5) were performed using:
- Independent Student's t-test for normally distributed variables
- Mann-Whitney U test for non-normal variables
- Categorical variables were compared using the Chi-square test.
- Correlations were analyzed using:
- Pearson correlation coefficient
- Spearman correlation where appropriate

To identify independent predictors of autonomic dysfunction and systolic BP variability, multiple linear regression analysis was performed with adjustment for:

- age,
- sex,
- body mass index,
- duration of diabetes,
- HbA1c,
- antihypertensive therapy,
- LDL cholesterol,
- Triglycerides.

A p-value < 0.05 was considered statistically significant.

Data Management: All data were entered into a structured Microsoft Excel spreadsheet and cross-verified for accuracy prior to statistical analysis. Missing values and outliers were assessed before analysis, and only complete datasets were included in the final evaluation.

Observations and Results: A total of 180 patients with type 2 diabetesmellitus aged 35–65 yearswere included in the study. The study population comprised 98 males (54.4%) and 82 females (45.6%). All participants completed the study protocol, including sleep quality assessment using the Pittsburgh Sleep Quality Index (PSQI), cardiovascular autonomic function testing, heart rate variability (HRV) analysis, and 24-hour ambulatory blood pressure monitoring (ABPM).

Demographic and Clinical Characteristics: The mean age of the study population was 52.8 ± 8.4 years, and the mean duration of diabetes was 7.6 ± 4.1 years. Males had significantly higher waist circumference and systolic blood pressure, whereas females showed slightly higher mean PSQI scores.

Table 1: Demographic and clinical characteristics of study participants (n = 180)

Variable	Males (n = 98)	Females (n = 82)	Total (n = 180)	p-value
Age (years)	53.2 ± 8.3	52.3 ± 8.5	52.8 ± 8.4	0.486
Duration of diabetes (years)	7.8 ± 4.3	7.3 ± 3.9	7.6 ± 4.1	0.412
Height (cm)	169.1 ± 6.7	156.8 ± 5.9	163.5 ± 8.7	<0.001
Weight (kg)	72.4 ± 10.8	65.8 ± 9.7	69.4 ± 10.7	<0.001
BMI (kg/m²)	25.3 ± 3.2	26.0 ± 3.5	25.6 ± 3.4	0.174
Waist circumference (cm)	92.6 ± 8.4	88.9 ± 8.1	90.9 ± 8.4	0.003
HbA1c (%)	8.1 ± 1.3	8.2 ± 1.4	8.1 ± 1.3	0.721
PSQI score	6.8 ± 3.0	7.4 ± 3.1	7.1 ± 3.1	0.182

Sleep Quality Distribution: The mean global PSQI score was 7.1 ± 3.1. Using the standard cutoff of PSQI >5, 123 participants (68.3%) were classified as poor sleepers.

Table 2: Distribution of sleep quality according to PSQI score

Sleep quality category	PSQI score	Number (n)	Percentage (%)
Good sleep quality	≤5	57	31.7
Poor sleep quality	>5	123	68.3
Total	—	**180**	**100.0**

Among poor sleepers, the most affected PSQI components were sleep latency, sleep duration, and daytime dysfunction.

Autonomic Function Test Results: Poor sleepers demonstrated significantly worse autonomic function compared with good sleepers across all Ewing's cardiovascular autonomic function tests.

Table 3: Comparison of autonomic function between good and poor sleepers

Parameter	Good sleepers (n = 57)	Poor sleepers (n = 123)	p-value
E:I ratio	1.24 ± 0.10	1.14 ± 0.09	<0.001
30:15 ratio	1.09 ± 0.08	1.01 ± 0.07	<0.001
Valsalva ratio	1.43 ± 0.16	1.28 ± 0.15	<0.001
Fall in SBP on standing (mmHg)	8.6 ± 4.1	13.4 ± 5.3	<0.001
Rise in DBP during handgrip (mmHg)	16.8 ± 4.6	12.1 ± 4.8	<0.001
Autonomic dysfunction score	**2.1 ± 1.2**	**4.8 ± 1.7**	**<0.001**

Poor sleepers had significantly higher autonomic dysfunction scores, indicating greater impairment of both parasympathetic and sympathetic cardiovascular reflexes.

Heart Rate Variability Analysis: Time-domain and frequency-domain HRV parameters were significantly reduced among poor sleepers.

Table 4: Heart rate variability parameters according to sleep quality

HRV parameter	Good sleepers (n = 57)	Poor sleepers (n = 123)	p-value
SDNN (ms)	42.6 ± 10.2	31.4 ± 8.9	<0.001
RMSSD (ms)	34.2 ± 9.4	24.1 ± 8.1	<0.001
pNN50 (%)	18.6 ± 7.8	10.2 ± 5.9	<0.001
LF power (ms²)	542 ± 168	486 ± 152	0.031
HF power (ms²)	396 ± 142	254 ± 118	<0.001
LF/HF ratio	1.37 ± 0.42	1.96 ± 0.55	<0.001

Poor sleep quality was associated with reduced parasympathetic activity (lower RMSSD and HF power) and relative sympathetic predominance (higher LF/HF ratio).

Ambulatory Blood Pressure Monitoring and Blood Pressure Variability: Participants with poor sleep quality exhibited significantly higher blood pressure variability indices and a greater prevalence of non-dipping blood pressure patterns.

Table 5: Ambulatory blood pressure and blood pressure variability

Parameter	Good sleepers (n = 57)	Poor sleepers (n = 123)	p-value
24-hour mean SBP (mmHg)	126.4 ± 10.8	132.8 ± 11.6	0.001
24-hour mean DBP (mmHg)	76.8 ± 7.2	80.2 ± 7.8	0.004
SD of 24-hour SBP (mmHg)	10.8 ± 2.9	14.6 ± 3.5	<0.001
SD of 24-hour DBP (mmHg)	8.1 ± 2.1	10.7 ± 2.6	<0.001
ARV-SBP (mmHg)	9.6 ± 2.5	12.8 ± 3.1	<0.001
ARV-DBP (mmHg)	7.2 ± 1.9	9.5 ± 2.3	<0.001
Nocturnal dipping (%)	11.2 ± 3.8	6.4 ± 3.5	<0.001

Nocturnal Blood Pressure Dipping Pattern: Poor sleepers had a markedly higher prevalence of non-dipping and reverse-dipping patterns.

Table 6: Nocturnal blood pressure dipping status

Dipping category	Good sleepers (n = 57)	Poor sleepers (n = 123)	Total (n = 180)
Normal dippers	39 (68.4%)	41 (33.3%)	80 (44.4%)
Non-dippers	16 (28.1%)	61 (49.6%)	77 (42.8%)
Reverse dippers	2 (3.5%)	21 (17.1%)	23 (12.8%)

The prevalence of abnormal nocturnal blood pressure patterns was significantly higher among poor sleepers ($\chi^2 = 21.6$, $p < 0.001$).

Correlation between Sleep Quality and Autonomic Dysfunction: Pearson correlation analysis revealed a significant positive correlation between PSQI score and autonomic dysfunction score.

Table 7: Correlation between sleep quality and autonomic function

Variable	Correlation coefficient (r)	p-value
PSQI vs Autonomic dysfunction score	**0.48**	**<0.001**
PSQI vs E:I ratio	**−0.41**	**<0.001**
PSQI vs 30:15 ratio	**−0.37**	**<0.001**
PSQI vsValsalva ratio	**−0.39**	**<0.001**

Higher PSQI scores were associated with greater autonomic impairment.

Correlation between Sleep Quality and Heart Rate Variability: Sleep quality demonstrated significant inverse correlations with major HRV indices.

Table 8: Correlation between PSQI score and HRV parameters

HRV parameter	Correlation coefficient (r)	p-value
SDNN	**−0.44**	**<0.001**
RMSSD	**−0.39**	**<0.001**
pNN50	**−0.35**	**<0.001**
HF power	**−0.42**	**<0.001**
LF/HF ratio	**0.33**	**<0.001**

These findings indicate that poorer sleep quality was associated with reduced vagal activity and increased sympathetic predominance.

Correlation between Sleep Quality and Blood Pressure Variability: Higher PSQI scores were significantly associated with increased blood pressure variability.

Table 9: Correlation between PSQI score and BP variability indices

BP variability parameter	Correlation coefficient (r)	p-value
SD of 24-hour SBP	**0.41**	**<0.001**
SD of 24-hour DBP	**0.36**	**<0.001**
ARV-SBP	**0.39**	**<0.001**
ARV-DBP	**0.34**	**<0.001**
Nocturnal dipping (%)	**−0.38**	**<0.001**

Poor sleep quality was associated with greater systolic and diastolic blood pressure variability and reduced nocturnal dipping.

Correlation Matrix of Major Study Variables

Table 10. Pearson correlation matrix

Variable	PSQI	Autonomic score	SDNN	RMSSD	SBP variability
PSQI score	1.00	0.48	−0.44	−0.39	0.41
Autonomic dysfunction score	0.48	1.00	−0.52	−0.46	0.43
SDNN	−0.44	−0.52	1.00	0.71	−0.38
RMSSD	−0.39	−0.46	0.71	1.00	−0.34
SBP variability	0.41	0.43	−0.38	−0.34	1.00

All displayed correlations were statistically significant at $p < 0.01$.

Multiple Linear Regression Analysis for Autonomic Dysfunction: A multiple linear regression model was constructed with autonomic dysfunction score as the dependent variable.

Table 11. Independent predictors of autonomic dysfunction

Predictor	Standardized β	Standard Error	t-value	p-value
PSQI score	**0.36**	0.07	5.18	**<0.001**
Age	0.14	0.03	2.02	0.045
Male sex	0.09	0.28	1.31	0.192
BMI	0.11	0.04	1.67	0.097
Duration of diabetes	0.19	0.05	2.86	0.005
HbA1c	0.23	0.09	3.24	0.001

Model statistics: $R^2 = 0.37$, Adjusted $R^2 = 0.35$, $F = 17.84$, $p < 0.001$

Multiple Linear Regression Analysis for Systolic Blood Pressure Variability

Table 12: Independent predictors of systolic BP variability

Predictor	Standardized β	Standard Error	t-value	p-value
PSQI score	**0.29**	0.18	3.42	**0.001**
Autonomic dysfunction score	**0.31**	0.27	3.68	**<0.001**
Age	0.12	0.11	1.52	0.130
BMI	0.10	0.13	1.28	0.202
HbA1c	0.18	0.22	2.31	0.022
Antihypertensive therapy	0.09	0.64	1.17	0.243

Model statistics: $R^2 = 0.33$, Adjusted $R^2 = 0.31$, $F = 14.66$, $p < 0.001$

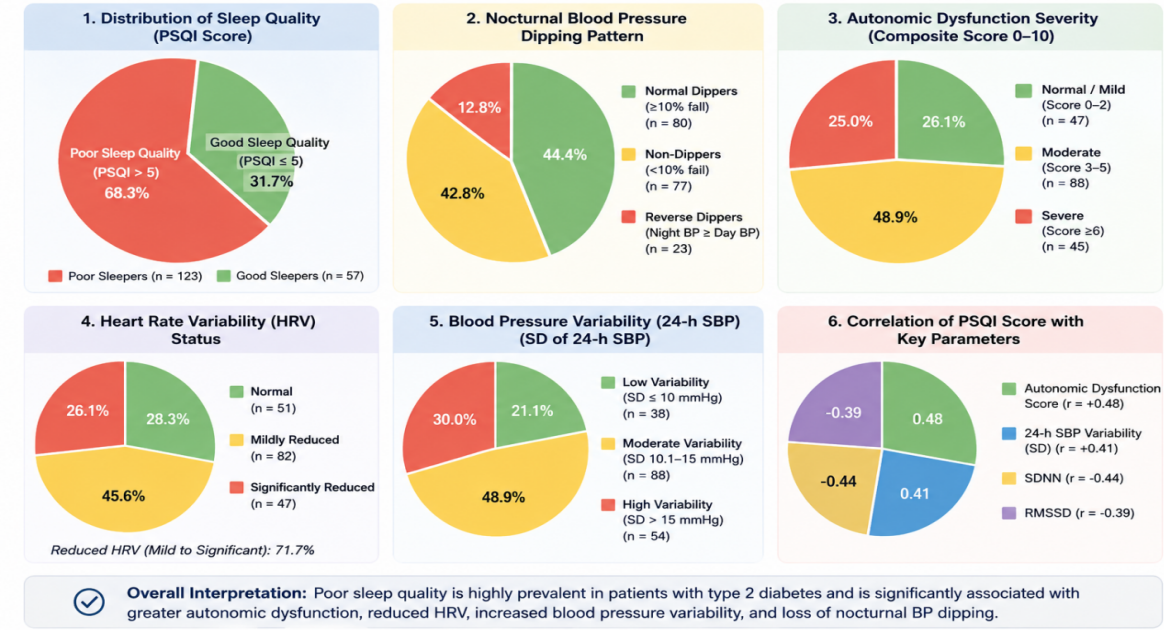

Figure 1:

Summary of Principal Findings: The present analysis showed that:

1. Poor sleep quality (PSQI >5) was present in 68.3% of patients with T2DM.
2. Poor sleepers exhibited significantly greater autonomic dysfunction.
3. Heart rate variability parameters indicating parasympathetic activity were significantly reduced among poor sleepers.
4. Poor sleep quality was associated with increased 24-hour blood pressure variability and reduced nocturnal dipping.
5. PSQI score remained an independent predictor of autonomic dysfunction and systolic blood pressure variability after adjustment for demographic and metabolic variables.

These findings support a significant association between sleep disturbance, autonomic dysfunction, and abnormal blood pressure variability in patients with type 2 diabetes mellitus, suggesting that impaired sleep may contribute to early cardiovascular autonomic impairment and altered circadian blood pressure regulation in this population.

Discussion

The present cross-sectional study evaluated the relationship between sleep quality, autonomic dysfunction, and blood pressure variability (BPV) in patients with type 2 diabetes mellitus (T2DM). [8] The principal findings were that poor sleep quality was highly prevalent among patients with T2DM and was significantly associated with greater autonomic dysfunction, reduced heart rate variability (HRV), increased blood pressure variability, and impaired nocturnal blood pressure dipping. Furthermore, sleep quality remained an independent predictor of autonomic dysfunction and systolic blood pressure variability after adjustment for age, sex, body mass index (BMI), duration of diabetes, HbA1c, and antihypertensive therapy.

These findings support the concept that sleep disturbance may contribute to cardiovascular autonomic impairment and abnormal blood

pressure regulation in T2DM, thereby increasing the risk of future cardiovascular complications.

Sleep Quality in Patients with Type 2 Diabetes Mellitus: In the present study, the mean global Pittsburgh Sleep Quality Index (PSQI) score was 7.1 ± 3.1, and 68.3% of participants were classified as poor sleepers (PSQI >5). This prevalence is consistent with previous reports indicating that sleep disturbances affect 40-70% of individuals with T2DM. [9] The most affected PSQI components in the present study were sleep latency, sleep duration, and daytime dysfunction, suggesting that diabetic patients experience difficulty initiating sleep, shortened sleep duration, and impaired daytime performance. [10]

Several mechanisms may explain the high prevalence of poor sleep quality in T2DM. Chronic hyperglycemia, nocturia, peripheral neuropathy, restless leg syndrome, obesity, obstructive sleep apnea, and psychological stress are common contributors. [11] In addition, alterations in circadian rhythm, inflammatory cytokines, and hypothalamic-pituitary-adrenal (HPA) axis activation may further impair sleep architecture. Sleep disruption may in turn worsen glycemic control, creating a bidirectional relationship between diabetes and poor sleep. [12]

Sleep Quality and Autonomic Dysfunction: The most important finding of the present study was the significant positive correlation between PSQI score and autonomic dysfunction score ($r = 0.48$, $p < 0.001$). Patients with poor sleep quality showed significantly lower E:I ratio, 30:15 ratio, and Valsalva ratio, along with abnormal blood pressure responses to standing and sustained handgrip, indicating impairment of both parasympathetic and sympathetic cardiovascular reflexes.

Diabetic autonomic neuropathy is a common complication of T2DM and results from chronic hyperglycemia-induced oxidative stress, advanced glycation end products, microvascular ischemia, and neuronal degeneration. [13] Early involvement of the vagus nerve leads to reduced parasympathetic activity, followed by progressive sympathetic dysfunction. [14] The higher autonomic dysfunction scores observed among poor sleepers suggest that sleep disturbance may either accelerate autonomic impairment or reflect underlying autonomic dysregulation.

Sleep deprivation and fragmented sleep are known to increase sympathetic nervous system activity, elevate circulating catecholamines, and reduce vagal tone. [15] Experimental studies have demonstrated increased norepinephrine levels, enhanced muscle sympathetic nerve activity, and reduced baroreflex sensitivity following sleep restriction. [16] These physiological changes may exacerbate the autonomic imbalance already present in T2DM.

The observed inverse correlations between PSQI score and E:I ratio, 30:15 ratio, and Valsalva ratio are clinically relevant because these tests are sensitive markers of early cardiac autonomic neuropathy. [17] Impairment of these reflexes has been associated with arrhythmias, silent myocardial ischemia, exercise intolerance, and increased cardiovascular mortality.

Sleep Quality and Heart Rate Variability: The present study showed significant inverse correlations between PSQI score and HRV indices, including SDNN ($r = -0.44$), RMSSD ($r = -0.39$), and HF power ($r = -0.42$), together with a positive correlation with LF/HF ratio ($r = 0.33$). These findings indicate that poor sleep quality is associated with reduced parasympathetic activity and relative sympathetic predominance.

Heart rate variability is a sensitive non-invasive marker of autonomic nervous system function and reflects beat-to-beat fluctuations in cardiac cycle length. Reduced SDNN indicates diminished overall autonomic modulation, while reduced RMSSD and HF power specifically reflect impaired vagal activity. [18] An elevated LF/HF ratio suggests sympathetic dominance or reduced parasympathetic influence.

Previous studies have consistently shown that both insomnia and short sleep duration are associated with reduced HRV, increased sympathetic activity, and impaired cardiovascular recovery during sleep. In diabetic patients, reduced HRV often precedes clinically apparent autonomic neuropathy and is considered an early predictor of cardiovascular events. [19] The present findings therefore suggest that poor sleep quality may identify diabetic individuals with early autonomic impairment before overt cardiovascular complications become evident.

Sleep Quality and Blood Pressure Variability: A major finding of the present study was the significant association between poor sleep quality and increased blood pressure variability. Higher PSQI scores correlated positively with 24-hour systolic BP variability ($r = 0.41$), diastolic BP variability ($r = 0.36$), ARV-SBP ($r = 0.39$), and ARV-DBP ($r = 0.34$), while showing a negative correlation with nocturnal dipping ($r = -0.38$).

Blood pressure variability reflects dynamic fluctuations in blood pressure resulting from interactions between autonomic nervous system activity, baroreflex function, vascular compliance, hormonal regulation, and behavioral factors. [20] Increased BPV has emerged as an independent predictor of stroke, myocardial infarction, left

ventricular hypertrophy, microalbuminuria, cognitive decline, and cardiovascular mortality.

Sleep plays a crucial role in maintaining normal circadian blood pressure regulation. During normal non-rapid eye movement (NREM) sleep, parasympathetic activity predominates, leading to reductions in heart rate, cardiac output, and blood pressure. Sleep fragmentation and reduced sleep duration interrupt this physiological pattern and result in persistent sympathetic activation, elevated nighttime blood pressure, and increased short-term BPV.

The higher prevalence of non-dipping and reverse-dipping patterns among poor sleepers observed in the present study is particularly important. Loss of nocturnal blood pressure dipping is strongly associated with diabetic nephropathy, retinopathy, cerebrovascular disease, and cardiovascular mortality. [21] These findings suggest that sleep disturbance may contribute to abnormal circadian blood pressure regulation in T2DM.

Relationship between Autonomic Dysfunction and Blood Pressure Variability: The correlation matrix showed that autonomic dysfunction score was positively associated with systolic blood pressure variability ($r = 0.43$), while HRV parameters were negatively associated with BP variability. [22] These observations are physiologically plausible because autonomic imbalance, particularly reduced vagal tone and increased sympathetic activity, directly influences short-term blood pressure fluctuations.

Impaired baroreceptor sensitivity is a hallmark of diabetic autonomic neuropathy. Baroreceptors normally buffer rapid changes in blood pressure through reflex modulation of heart rate and vascular tone. Reduced baroreflex sensitivity results in exaggerated blood pressure fluctuations and diminished cardiovascular adaptability. [23] Thus, autonomic dysfunction provides a mechanistic link between poor sleep quality and increased BP variability.

Independent Effect of Sleep Quality: One of the strengths of the present study is the use of multiple linear regression analysis, which showed that PSQI score remained an independent predictor of autonomic dysfunction ($\beta = 0.36$, $p < 0.001$) and systolic blood pressure variability ($\beta = 0.29$, $p = 0.001$) after adjustment for important confounding variables.

These findings indicate that the relationship between sleep quality and cardiovascular autonomic impairment is not solely explained by age, obesity, duration of diabetes, glycemic control, or antihypertensive therapy. [24]

Rather, sleep quality appears to have an independent association with autonomic regulation and blood pressure dynamics. The regression analysis also identified HbA1c and duration of diabetes as additional predictors of autonomic dysfunction, supporting the established role of chronic hyperglycemia and cumulative metabolic injury in diabetic autonomic neuropathy. [25]

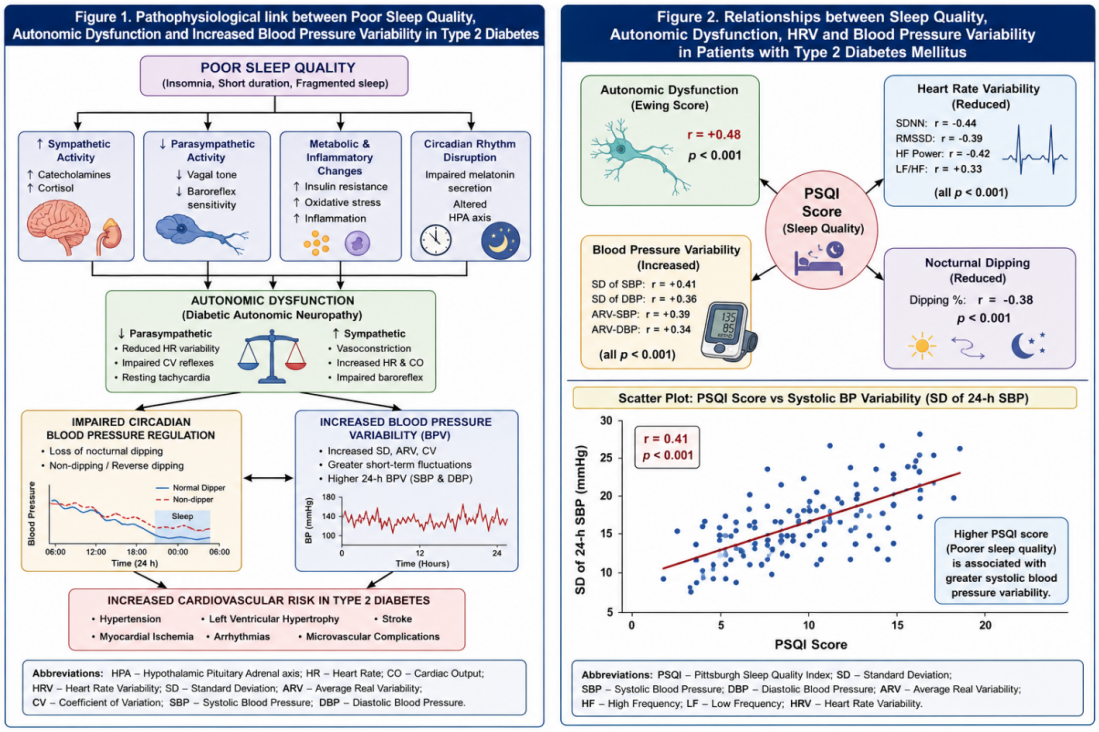

Figure 2:

Comparison with Previous Studies: The present findings are consistent with numerous clinical investigations. Spallone and colleagues have emphasized that cardiac autonomic neuropathy is one of the strongest predictors of mortality in diabetes and is closely associated with reduced HRV. [26] Vinik et al. demonstrated that autonomic dysfunction may occur early in the course of T2DM and often remains clinically unrecognized.

Studies evaluating sleep quality in diabetic populations have reported that poor sleep is associated with higher HbA1c levels, reduced HRV, increased sympathetic activity, and impaired endothelial function. Similar associations between PSQI scores and autonomic dysfunction have been observed in patients with diabetes, metabolic syndrome, and hypertension. [27]

Research using 24-hour ambulatory blood pressure monitoring has shown that diabetic patients frequently exhibit increased BP variability and reduced nocturnal dipping, both of which are linked to autonomic neuropathy and cardiovascular complications. [28] The present study extends these observations by simultaneously examining sleep quality, autonomic function, HRV, and BP variability, thereby providing a more integrated assessment of cardiovascular autonomic regulation.

Clinical Significance: The clinical implications of these findings are substantial. Poor sleep quality is common, easily assessable, and potentially modifiable. The Pittsburgh Sleep Quality Index is inexpensive, simple to administer, and can be incorporated into routine diabetic care. [29]

Identification of poor sleep quality may help clinicians recognize patients who are at increased risk of cardiac autonomic neuropathy, abnormal blood pressure variability, and future cardiovascular events. Early interventions including sleep hygiene education, treatment of insomnia, screening for obstructive sleep apnea, weight reduction, physical activity, stress management, and optimization of glycemic control may improve autonomic function and cardiovascular outcomes.

Strengths of the Study

The present study has several strengths:

1. Comprehensive assessment of sleep quality, autonomic function, HRV, and ambulatory blood pressure variability.
2. Use of validated instruments including PSQI, Ewing's cardiovascular autonomic function tests, and ABPM.
3. Evaluation of both parasympathetic and sympathetic autonomic function.
4. Assessment of circadian blood pressure patterns.
5. Multivariable regression analysis controlling for major metabolic and demographic confounders.

Conclusion

The present study showed that poor sleep quality was highly prevalent among patients with type 2 diabetes mellitus and was significantly associated with autonomic dysfunction and increased blood pressure variability.

Higher Pittsburgh Sleep Quality Index (PSQI) scores showed significant positive correlations with autonomic dysfunction score and systolic blood pressure variability, together with significant negative correlations with heart rate variability indices including SDNN, RMSSD, and HF power. Patients with poor sleep quality also exhibited a markedly higher prevalence of non-dipping and reverse-dipping nocturnal blood pressure patterns, indicating impaired circadian blood pressure regulation.

Importantly, sleep quality remained an independent predictor of autonomic dysfunction and systolic blood pressure variability after adjustment for age, sex, body mass index, duration of diabetes, HbA1c, and antihypertensive therapy. These findings support the hypothesis that sleep disturbance may contribute to sympathetic predominance, reduced parasympathetic activity, impaired cardiovascular autonomic regulation, and abnormal blood pressure dynamics in T2DM.

The results suggest that assessment of sleep quality should be incorporated into routine evaluation of patients with type 2 diabetes mellitus, as poor sleep may identify individuals at increased risk of cardiac autonomic neuropathy, increased blood pressure variability, and future cardiovascular complications. Early interventions aimed at improving sleep quality may represent a practical and potentially modifiable strategy for reducing cardiovascular risk in diabetic populations.

Recommendations for Future Research

1. Prospective longitudinal studies to determine whether poor sleep quality predicts progression of autonomic neuropathy and cardiovascular events in T2DM.
2. Randomized controlled trials evaluating the effect of sleep improvement interventions on HRV and blood pressure variability.
3. Multicenter studies involving larger and ethnically diverse diabetic populations.
4. Studies incorporating polysomnography, continuous nocturnal HRV monitoring, inflammatory biomarkers, oxidative stress markers, and endothelial function assessment.

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