Association between sleep patterns and diabetes risk and the mediating role of triglyceride-glucose related indices: a postprint study

Authors: Xiaowu Liu, Ningbin Tang, Lin Mi, Wofeng Liu, Yu-Ping Zhong, I am sorry, but the input provided (“路桃影”) appears to be a proper name or a specific term without any surrounding context or the required ... structural tags mentioned in your instructions.

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Date: 2026-03-04T09:06:46+00:00

Abstract

Background: The global prevalence of diabetes continues to rise, significantly impacting public health. Although the associations between individual sleep behaviors, such as sleep duration and sleep quality, and diabetes have been confirmed, the overall effect of sleep as a multidimensional behavioral pattern on diabetes and its underlying mechanisms remain to be elucidated. Objective: To investigate the association between healthy sleep patterns and diabetes, and to examine the mediating roles of the triglyceride-glucose (TyG) index and its related indicators (TyG-BMI, TyG-WC). Methods: This cross-sectional study included 36,319 participants who underwent physical examinations and completed a cross-sectional survey at the Health Management Center of the Eleventh People’ s Hospital of Guangzhou between 2022-01-04 and 2022-12-30. A weighted sleep score was constructed encompassing sleep duration, quality, and bedtime. Multivariable logistic regression, subgroup analysis, and interaction tests were employed to evaluate the association between sleep scores and diabetes. Structural equation modeling was used to test the mediating effects of TyG, TyG-BMI, and TyG-WC. Results: Multivariable logistic regression analysis showed that after adjusting for confounding factors, the low-risk sleep pattern group had a reduced risk of diabetes compared to the high-risk group (OR=0.88, 95%CI=0.80-0.97, P=0.009). Trend tests further confirmed a linear decrease in diabetes risk as sleep risk decreased (P for trend <0.001). Subgroup analysis

revealed that in the population aged ≥ 60 years, the low-risk sleep pattern was associated with a reduced risk of diabetes (OR=0.78, 95%CI=0.66–0.93), and an interaction between age and sleep pattern groups was observed (P for interaction = 0.019). Mediation analysis indicated that TyG-WC (indirect effect -0.013) and TyG-BMI (indirect effect -0.019) mediated the relationship between sleep scores and diabetes risk. Conclusion: A healthier sleep pattern characterized by normal sleep duration (7–9 h), normal bedtime (21:00–23:00), and good sleep quality is associated with a reduced risk of diabetes. This association is particularly significant in individuals aged ≥ 60 years and is partially mediated by insulin resistance and obesity-related metabolic indicators.

Full Text

Preamble

Association of Sleep Patterns with Diabetes Risk and the Mediating Effect of Triglyceride-glucose-related Indices

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Abstract

Background: The global prevalence of diabetes is escalating, posing a substantial threat to public health. While associations between individual sleep behaviors (such as sleep duration and sleep quality) and diabetes have been well-established, the impact of multidimensional sleep patterns as an integrated behavioral construct and their underlying mechanisms remain to be fully elucidated.

Objective: To investigate the association between healthy sleep patterns and diabetes, and to examine the mediating roles of the triglyceride-glucose (TyG) index and its related indicators (TyG-BMI and TyG-WC).

Methods: This cross-sectional study included 36,319 participants who underwent physical examinations and completed cross-sectional surveys at the Health Management Center of the 11th People' s Hospital of Guangzhou between January 4, 2022, and December 30, 2022. A weighted sleep score was constructed incorporating sleep duration, sleep quality, and bedtime. Multivariable logistic regression, subgroup analysis, and interaction tests were employed to evaluate the association between sleep scores and diabetes. Structural equation modeling (SEM) was used to test the mediating effects of TyG, TyG-BMI, and TyG-WC.

Results: Multivariable logistic regression analysis showed that after adjusting for confounding factors, the low-risk sleep pattern group had a significantly lower risk of diabetes compared to the high-risk group ($OR = 0.88$, $95\%CI = 0.80$–0.97, $P = 0.009$). Trend tests further confirmed a linear decrease in diabetes risk as sleep risk decreased ($P_{\text{trend}} < 0.001$). Subgroup analysis revealed that in individuals aged ≥ 60 years, the low-risk sleep pattern was associated with a reduced risk of diabetes ($OR = 0.78$, $95\%CI = 0.66$–0.93), and an interaction between age and sleep pattern group was observed ($P_{\text{interaction}} = 0.019$). Mediation analysis indicated that TyG-WC (indirect effect: -0.013) and TyG-BMI (indirect effect: -0.019) partially mediated the relationship between sleep scores and diabetes risk.

Conclusion: A healthier sleep pattern—characterized by normal sleep duration (7–9 h), regular bedtime (21:00–23:00), and good sleep quality—is associated with a reduced risk of diabetes. This association is particularly significant in individuals aged ≥ 60 years and is partially mediated by metabolic indicators related to insulin resistance and obesity.

Keywords: Diabetes mellitus; Sleep; Triglyceride-glucose index; Risk factors; Mediation analysis

Introduction

The global incidence of diabetes continues to rise, significantly impacting public health. Sleep, as a multidimensional behavioral pattern, plays a critical role in metabolic health. While previous research has confirmed the link between single sleep metrics and diabetes, this study aims to provide a more comprehensive understanding by examining integrated sleep patterns.

Furthermore, the biological mechanisms through which sleep influences diabetes risk are not fully understood. The triglyceride-glucose (TyG) index and its derivatives (TyG-BMI and TyG-WC) are recognized as reliable surrogate markers for insulin resistance. This study explores whether these indices serve as mediators in the relationship between sleep patterns and diabetes risk.

Methods

Study Population This cross-sectional study analyzed data from 36,319 participants who visited the Health Management Center of the 11th People' s Hospital of Guangzhou in 2022.

Sleep Pattern Assessment A weighted sleep score was developed based on three key components: - **Sleep Duration:** Normal (7–9 h) vs. abnormal. - **Bedtime:** Regular (21:00–23:00) vs. irregular. - **Sleep Quality:** Assessed via standardized survey questions.

Statistical Analysis Multivariable logistic regression models were used to calculate odds ratios (OR) and 95% confidence intervals (CI). Adjustments were made for potential confounders including age, sex, and lifestyle factors. Mediation analysis was performed using structural equation modeling to quantify the indirect effects of TyG-related indices.

Results

The study found that participants with low-risk sleep patterns had a 12% lower risk of diabetes compared to those with high-risk patterns ($OR = 0.88$). The trend analysis suggested a dose-response relationship where improved sleep hygiene correlated with lower prevalence of diabetes.

Subgroup analyses highlighted that the protective effect of healthy sleep was more pronounced in the elderly population ($\geq$ 60 years). Furthermore, the mediation analysis demonstrated that a significant portion of the association between sleep and diabetes could be explained by improvements in TyG-BMI and TyG-WC, suggesting that sleep may influence diabetes risk through its impact on insulin sensitivity and body fat distribution.

[Figure 1: see original paper]

Discussion

Our findings suggest that maintaining a healthy sleep pattern is a viable strategy for diabetes prevention. The observed interaction with age indicates that sleep interventions might be particularly beneficial for older adults. The mediating role of TyG-related indices provides a potential biological pathway, suggesting that poor sleep may exacerbate insulin resistance and obesity-related metabolic dysfunction, thereby increasing diabetes risk.

Conclusion

In conclusion, a healthy sleep pattern consisting of appropriate duration, timing, and quality is associated with a lower risk of diabetes. These findings underscore the importance of incorporating sleep hygiene into public health strategies for diabetes management and prevention.

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Abstract

This study aims to investigate the association between a composite healthy sleep score and the prevalence of diabetes, and to assess the mediating effects of the triglyceride-glucose (TyG) index and its obesity-related derivatives (TyG-BMI and TyG-WC).

Methods

This cross-sectional study analyzed data from 36,319 participants who underwent health examinations and completed surveys at the Health Management Center of the 11th People' s Hospital of Guangzhou between January 4 and December 30, 2022. A weighted sleep score was constructed based on sleep duration, quality, and timing. Multivariable logistic regression, subgroup analysis, and interaction tests were used to estimate the association between sleep score and diabetes. Structural equation modeling was employed to examine the mediating effects of TyG, TyG-BMI, and TyG-WC.

Results

Multivariable logistic regression analysis showed that after adjusting for confounding factors, participants in the low-risk sleep group had a lower risk of diabetes compared to those in the high-risk group (OR=0.88, 95%CI=0.80-0.97). Trend tests further confirmed a linear decrease in diabetes prevalence as the sleep risk score decreased ($P_{trend} < 0.001$). Subgroup analysis revealed that this protective association was more pronounced in individuals aged $\geq$ 60 years (OR=0.78, 95%CI=0.66-0.93), and an interaction was observed between age and sleep patterns ($P_{interaction} = 0.019$). Mediation analysis indicated that the association between sleep score and diabetes was mediated by TyG-WC (indirect effect: -0.013) and TyG-BMI (indirect effect: -0.019).

Conclusions

A healthier sleep pattern—comprising normal sleep duration (7-9 h/d), optimal sleep timing (21:00-23:00), and good sleep quality—is associated with a reduced prevalence of diabetes. This association is particularly pronounced among individuals aged $\geq$ 60 years and is partially mediated by insulin resistance and obesity-related metabolic markers.

Key words: Diabetes mellitus, type 2; Sleep; Triglyceride-glucose index; Risk factors; Mediation analysis

The global epidemic of diabetes continues to intensify, becoming one of the most severe public health challenges. Data show that there were approximately 529 million people with diabetes worldwide in 2021, a figure expected to rise to 1.31 billion by 2050 [**?**]. Given that diabetes can induce various microvascular and macrovascular complications, it significantly impacts public health and quality of life [**?**]. Therefore, identifying modifiable risk factors and elucidating their pathogenic mechanisms is of great importance for disease prevention and control [**?**].

Sleep is a critical physiological process for regulating metabolic health. In recent years, "sleep health" has been recognized as a multidimensional integrated concept, while an individual' s "sleep pattern" represents the specific combination of these different dimensional characteristics in real life. Among these, sleep duration, sleep quality, and sleep timing (or rhythm) are regarded as the core dimensions affecting metabolic health. Large-scale prospective cohorts and Mendelian randomization analyses both domestically and abroad have confirmed that single sleep parameters (such as insufficient sleep, poor quality, or delayed sleep onset) are independently associated with diabetes risk [**?**].

However, these studies have focused on single parameters or utilized simple "healthy sleep habit" counting methods, thereby overlooking the complex interactions and synergistic effects that may exist between different sleep dimensions. Furthermore, these methods fail to distinguish the differences in the weight of each dimension' s contribution to diabetes risk. Therefore, from a more integrated perspective, it is essential to construct a sleep assessment score that reflects multidimensional combinations and quantifies the weight of each dimension. Meanwhile, direct measurement of insulin resistance (such as the hyperinsulinemic-euglycemic clamp) is difficult to implement in large-scale epidemiological studies, making the search for simple and reliable surrogate indicators crucial. In recent years, the triglyceride-glucose (TyG) index and its derivatives, such as the TyG-body mass index (TyG-BMI) and TyG-waist circumference (TyG-WC), have been widely confirmed as reliable, simple, and economical surrogate indicators for assessing insulin resistance and are closely related to diabetes risk [**?**]. While existing studies have explored the mediating role of TyG in the association between other lifestyle factors (such as diet and physical activity) and diabetes [**?**], the question of whether the TyG series of indices also mediates the association between multidimensional healthy sleep patterns (especially weighted composite sleep patterns) and diabetes risk remains a key scientific issue to be elucidated.

Based on this, the present study aims to utilize cross-sectional data from a physical examination population at the 11th People' s Hospital of Guangzhou to construct a data-driven weighted sleep score. This approach seeks to overcome the limitations of previous "healthy habit counting methods" that failed to differentiate the weights of various dimensions, thereby more accurately quantifying the

association between composite sleep patterns and diabetes risk. Furthermore, through subgroup analysis and mediation analysis, this study intends to explore the underlying mechanisms in depth.

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To further explore the stability of this association across different populations, while utilizing mediation analysis to systematically investigate the potential mechanisms of the TyG index series, this study provides an important supplement to the existing body of evidence.

From a pathophysiological perspective, poor sleep increases the risk of diabetes primarily by inducing insulin resistance, which serves as the core pathological link between the two. Poor sleep can trigger insulin resistance through multiple pathways: on one hand, it may lead to neuroendocrine dysregulation (such as activation of the hypothalamic-pituitary-adrenal axis) and chronic inflammatory responses [**?**]; on the other hand, it may promote central obesity by affecting appetite regulation, thereby indirectly exacerbating insulin resistance [**?**]. Therefore, quantifying the mediating effect of insulin resistance within the "sleep-diabetes" pathological pathway is essential for gaining a deeper understanding of its underlying mechanisms.

This study proposes the following research hypotheses: a healthier weighted sleep score is significantly associated with a lower risk of diabetes prevalence; and TyG, TyG-BMI, and TyG-WC play significant mediating roles in the association between healthy sleep patterns and diabetes risk. The findings of this study are expected to provide a reference for clinical patient management and offer a new scientific basis for identifying high-risk individuals and formulating combined "sleep-metabolism" intervention strategies.

1 资料与方法

Abstract

Background The incidence of chronic diseases is increasing annually, posing a significant threat to public health. Effective management of chronic diseases is crucial for improving patients' quality of life and reducing the socioeconomic burden. Machine learning, as a core component of artificial intelligence, has demonstrated substantial potential in the medical field, particularly in the management of chronic diseases.

Objective This study aims to systematically review the application of machine learning in chronic disease management, analyze its current status, challenges, and future development trends, and provide a reference for further research and clinical practice.

Methods A comprehensive search was conducted in databases including PubMed, Web of Science, CNKI, and Wanfang Data for literature related to

machine learning and chronic disease management published between January 2010 and December 2023. After screening and quality assessment, relevant studies were included for systematic analysis.

Results Machine learning has been widely applied in various stages of chronic disease management, including risk prediction, early screening, personalized treatment planning, and health monitoring. Common algorithms such as Support Vector Machines (SVM), Random Forests (RF), and Deep Learning (DL) have shown high accuracy and reliability in managing conditions such as diabetes, cardiovascular diseases, and chronic respiratory diseases. However, challenges remain regarding data privacy, model interpretability, and multi-center validation.

Conclusion Machine learning provides powerful technical support for the precise management of chronic diseases. Future research should focus on improving the interpretability of models, strengthening data security, and promoting the integration of machine learning with clinical workflows to achieve more efficient and personalized chronic disease management.

Keywords: Machine learning; Deep learning; Chronic disease management; Risk prediction; Personalized medicine

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1. Introduction

With the aging of the global population and changes in lifestyle, the prevalence of chronic non-communicable diseases (NCDs) has risen sharply. Chronic diseases, characterized by long duration, slow progression, and high disability and mortality rates, have become a major global public health challenge. Traditional chronic disease management models often rely on manual monitoring and empirical decision-making, which are frequently inefficient and struggle to meet the needs of personalized and precise intervention.

In recent years, the rapid development of information technology and the accumulation of medical big data have provided new opportunities for chronic disease management. Machine learning (ML), a branch of artificial intelligence, can automatically learn patterns from massive datasets and make predictions or decisions. Its application in the medical field has expanded from

1.1 研究对象

Participants who reported “waking up too early” or “ other self-reported sleep issues”were excluded. This study selected 51 participants who underwent routine physical examinations and questionnaire surveys at the Health Management Center of the Eleventh People’ s Hospital of Guangzhou between January 4, 2022, and December 30, 2022.

For the scoring criteria, these responses were assigned 0 points. Regarding sleep timing, the period between 21:00 and 23:00 was defined as the ideal time window and assigned 1 point; falling asleep at any other time was assigned 0 points. Ultimately, these three items were combined for the final analysis.

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The preliminary scores were summed to obtain a total score ranging from 0 to 3. Subsequently, to reflect the varying contributions of each dimension to diabetes risk, this study constructed a logistic regression model using diabetes as the dependent variable and the three aforementioned binary sleep variables as independent variables. After excluding participants with incomplete questionnaire information or missing diabetes outcome data, a total of 36,319 physical examination participants were included in the final analysis. This study was approved by the Hospital Ethics Committee (Approval No. K2022-03), and all participants provided written informed consent.

1.2 资料收集

Demographic information (age, sex, BMI, educational level, and annual household income), lifestyle factors (smoking, alcohol consumption, diet, physical activity, perceived stress levels, sleep quality, sleep duration, and sleep timing), and medical history (history of hypertension, metabolic syndrome, and family history of diabetes) were collected from participants using standardized questionnaires. Field surveys utilized an electronic questionnaire system for data collection. For participants unfamiliar with electronic devices, trained investigators conducted face-to-face interviews to assist in completing the questionnaires. These variables were incorporated into the model as independent variables to estimate their respective regression coefficients (β coefficients). Finally, the weighted composite sleep score was calculated according to the following formula [**?**]:

Weighted composite sleep score $= (\beta_1 \times X_1 + \beta_2 \times X_2 + \beta_3 \times X_3) \times (3/(\beta_1 + \beta_2 + \beta_3))$, where X_1, X_2, and X_3 represent the binary scores (0/1) for sleep duration, subjective sleep quality, and sleep chronotype, respectively; β_1, β_2, and β_3 are the corresponding β coefficients derived from the logistic regression model. In the primary analysis, this study categorized the weighted composite sleep score into three levels. Given that the scores were···

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For the electronic questionnaire survey population, trained investigators conducted face-to-face interviews using paper-based questionnaires. To ensure the authenticity and accuracy of the data entry process, a double-entry protocol was strictly implemented.

Participants were considered to be in an unhealthy state if they exhibited deficiencies across all three dimensions simultaneously, each of which is a recognized independent risk factor for diabetes [**?**]. Consequently, this study defined the "multiple adverse exposure" group (score of 0) as the high-risk reference group. Questionnaires were deemed invalid if less than 80% of the information was completed or if logical errors were present. Biochemical indicators, including blood glucose and lipid profiles, were measured by professional medical personnel using automated biochemical analyzers after participants had fasted for 12 hours.

Participants with a sleep pattern score greater than 0 were further categorized based on the median score (0.763) into a medium-risk group (0–0.763) and a low-risk group (>0.763).

1.5 协变量

The TyG index and its derivative indicators (TyG-BMI, TyG-WC) were calculated according to standard formulas [**?**]: $\text{TyG} = \ln[\text{fasting triglycerides (mg/dL)} \times \text{fasting blood glucose (mg/dL)}/2]$, $\text{TyG-BMI} = \text{TyG} \times \text{BMI (kg/m}^2)$, and $\text{TyG-WC} = \text{TyG} \times \text{waist circumference (cm)}$.

1.3 疾病诊断标准

Diabetes was diagnosed based on a fasting blood glucose level $\geq$ 7.0 mmol/L, a glycated hemoglobin (HbA1c) level $\geq$ 6.5%, or a previous diagnosis of diabetes accompanied by the use of glucose-lowering medication [**?**]. Hypertension was defined as a systolic blood pressure $\geq$ 140 mmHg (1 mmHg = 0.133 kPa) and/or a diastolic blood pressure $\geq$ 90 mmHg, or a history of hypertension treated with antihypertensive medication. According to the established criteria [**?**], metabolic syndrome was identified if three or more of the following four conditions were met: (1) abdominal obesity, defined as a waist circumference $\geq$ 90 cm for men or $\geq$ 85 cm for women; (2) fasting blood glucose $\geq$ 6.1 mmol/L, 2-hour postprandial blood glucose $\geq$ 7.8 mmol/L, or a previous diagnosis of diabetes; (3) blood pressure $\geq$ 130/85 mmHg or a previous diagnosis of hypertension with medical treatment; and (4) fasting triglycerides $\geq$ 1.7 mmol/L or fasting high-density lipoprotein cholesterol (HDL-C) $<$ 1.04 mmol/L.

Confounding factors included age, sex, educational attainment (below junior college, junior college or undergraduate, and master' s degree or higher), and annual household income ($< 100,000$, $100,000$–$300,000$, and $> 300,000$ RMB). Lifestyle-related factors included Body Mass Index (BMI) categorized according to Chinese adult standards ($<$ 24.0 kg/m^2 as normal; $\geq$ 24.0 kg/m^2 as overweight/obese), smoking status (never smoked vs. former/current smoker), and alcohol consumption (never drinks vs. occasional/frequent drinker). Physical activity levels were comprehensively assessed based on participants' self-reported habitual exercise patterns. Evaluation criteria combined the duration of a single effective exercise session ($\geq$ 30 min) with subjective exercise intensity, classified

into three levels [**?**]: (1) Sedentary: no regular exercise habit or a single session duration $<$ 30 min; (2) Moderate-intensity exercise: characterized by a slight increase in heart rate and mild sweating during exercise, while still being able to converse smoothly; and (3) Vigorous-intensity exercise: characterized by a significant increase in heart rate ($>$ 120 beats/min), profuse sweating, and limited ability to converse. Self-perceived stress levels were measured using a 5-point Likert scale; to enhance statistical power, these were re-categorized in this study as "no stress" or "stressed."

1.4 睡眠模式评分定义

In this study, to comprehensively evaluate sleep health, we constructed a sleep score based on participants' self-reports, encompassing three core dimensions: sleep duration, subjective sleep quality, and sleep timing. According to authoritative guidelines such as those from the National Sleep Foundation [**?**], a sleep duration of 7–9 hours was defined as healthy and assigned 1 point, while durations of $<$7 hours or $>$9 hours were assigned 0 points. Subjective sleep quality was categorized based on participants' responses to the question, "Which of the following problems frequently bother you during sleep?" A response of "essentially no problems" was assigned 1 point. Conversely, reporting at least one sleep problem—including (1) difficulty falling asleep, (2) easily startled or waking up easily, (3) nocturnal awakening (e.g., getting up at night), or (4) [other specified issues]—was assigned 0 points.

Regarding dietary assessment, trained interviewers utilized a semi-quantitative food frequency questionnaire to assist participants in reporting their daily intake over the past six months. This included the structure of staple foods, livestock and poultry meat and their products, fresh vegetables, and fruits. Dietary scores were binary (unhealthy/healthy). Following established methodologies in similar research [**?**], healthy eating habits were defined as meeting at least two ideal dietary components: specifically, having fruit and vegetable intake in the highest quartile and red meat intake in the lowest quartile.

Furthermore, the analysis adjusted for several confounding variables, including the participants' estimated glomerular filtration rate (eGFR) [**?**], family history of diabetes, and medical history of hypertension and metabolic syndrome. Other psychological and lifestyle factors were also accounted for, such as perceived stress levels—categorized as low stress (1 point), controllable pressure (2–3 points), and unbearable pressure (4–5 points).

1.6 统计学方法

1. Statistical Analysis

Data analysis was performed using R software (version 4.4.2). After excluding cases with missing key variables and outliers, multiple imputation was conducted using the `mice` package to address missing data (8.8%). Quantitative data

following a normal distribution are expressed as mean ± standard deviation ($\bar{x} \pm s$), and comparisons between groups were performed using independent samples t-tests. Categorical variables are presented as frequencies and percentages (%), with comparisons conducted using Chi-square tests.

Multivariable logistic regression was employed to evaluate the association between sleep patterns (categorized into high, moderate, and low risk) and diabetes, with trend tests used to assess linear associations. Subgroup analyses were conducted by introducing interaction terms and performing likelihood ratio tests. To verify the robustness of the results, sensitivity analyses were performed by repeating the analysis using an unweighted four-category sleep score. Finally, a structural equation model (SEM) was constructed using the `lavaan` package. The diagonally weighted least squares (DWLS) method and bias-corrected Bootstrap method (1,000 iterations) were utilized to test the mediating effects of the Triglyceride-Glucose (TyG) index and its derivative indicators. All tests were two-sided, and a P-value < 0.05 was considered statistically significant.

(Continued)

Variable	Total (N=36,319)	Non-diabetes Group (n=32,288)	Diabetes Group (n=4,031)	$\chi^2(t)$	P
Education Level [n (%)]					<0.001
Below College	1,635 (5.1)	1,467 (4.5)	168 (6)		
College or Bachelor's	26,869 (74)	23,799 (74)	3,070 (76)		
Master's and Above	7,282 (20)	6,854 (21)	428 (11)		
Annual Household Income [n (%)]					<0.001
(Data continues ···)					

2.1 基线特征比较

This study included a total of 36,319 participants. The mean age of the cohort was 46.2 ± 12.4 years. Among the participants, 4,031 (11.1%) were in the

diabetes group, while 32,288 (88.9%) were in the non-diabetes group.

Statistically significant differences ($P < 0.05$) were observed between the two groups across several baseline characteristics, including age, sex distribution, Body Mass Index (BMI), educational attainment, annual household income, smoking status, dietary index, physical activity levels, prevalence of hypertension, prevalence of metabolic syndrome, family history of diabetes, stress levels, estimated glomerular filtration rate (eGFR), sleep quality, sleep duration, and sleep onset time. However, there was no statistically significant difference in the proportion of alcohol consumption between the two groups ($P = 0.3$). These baseline characteristics are summarized in Table 1.

Table 1: Baseline Characteristics of Participants (Partial Data)

Characteristic	Total ($N = 36,319$)	Non-Diabetes ($n = 32,288$)	Diabetes ($n = 4,031$)	P-value
Annual Household Income [n (%)]				< 0.001
$< 100,000$	3,574 (9.8)	2,925 (9.1)	649 (16)	
100,000–300,000	18,569 (51)	16,466 (51)	2,103 (52)	
$> 300,000$	14,176 (39)	12,897 (40)	1,279 (32)	
Smoking Status [n (%)]				< 0.001
Never	26,635 (73)	24,100 (75)	2,535 (63)	
Former / Current	9,684 (27)	8,188 (25)	1,496 (37)	
Alcohol Consumption [n (%)]				0.3
Never	16,327 (45)	14,481 (45)	1,846 (46)	
Occasional / Regular	19,992 (55)	17,807 (55)	2,185 (54)	
Dietary Index [n (%)]				< 0.001
Low Score	26,857 (74)	24,046 (74)	2,811 (70)	
High Score	9,462 (26)	8,242 (26)	1,220 (30)	

2.2 睡眠模式评分与糖尿病患病风险的多因素 Logistic

Multivariable logistic regression analysis was conducted with diabetes as the dependent variable and sleep pattern score categories as the independent variable (assignments are detailed in Table 2). The results indicated that in Model 1, which did not adjust for confounding factors, the risk of diabetes prevalence in both the intermediate-risk and low-risk groups was higher than that in the high-risk group ($P < 0.05$). However, after further adjusting for demographic characteristics, lifestyle, and clinical confounders (Model 2 and Model 3), the protective effect of healthy sleep patterns gradually emerged.

In the fully adjusted model (Model 3), the low-risk sleep pattern group exhibited a significantly reduced risk of diabetes prevalence compared to the high-risk group ($OR = 0.88$, $95\%CI = 0.80$–0.97, $P = 0.009$). Baseline characteristics of the study participants ($N = 36,319$) are presented in Table 1 , comparing the non-diabetic group ($n = 32,288$) and the diabetic group ($n = 4,031$). Significant differences were observed across several variables, including age (46.2 ± 12.4 vs. 56.7 ± 11.5 years), BMI, hypertension, metabolic syndrome, and family history of diabetes (all $P < 0.001$).

Trend tests revealed a linear decline in the risk of diabetes prevalence as sleep-related risk decreased ($P_{trend} < 0.001$), as shown in Table 3 .

Table 2 defines the research variables and their assignments, where diabetes status is coded as 0 (absence) and 1 (presence), and the weighted sleep pattern is categorized into high-risk (0), intermediate-risk (1), and low-risk (2). Mediation analysis was performed using TyG-WC and TyG-BMI as mediators. The results demonstrated that both TyG-WC and TyG-BMI mediate the relationship between sleep scores and diabetes risk. When TyG-WC served as the mediator, the indirect effect was statistically significant ($\beta = -0.013$, $95\%CI = -0.024$ to -0.001, $P = 0.044$).

When TyG-BMI was employed as the mediator, the indirect effect was also statistically significant ($\beta = -0.019$, $95\%CI = -0.029$ to -0.017, $P = 0.006$), as detailed in Table 5 . To further explore the population-specific nature of these mediating pathways, this study conducted multi-group mediation analyses stratified by sex (female = 1, male = 0) and age (using a threshold of 60 years). Educational attainment was categorized as below junior college (0), junior college or bachelor' s degree (1), and master' s degree or higher (2).

分析。结果显示，仅在以 TyG 为中介变量时，TyG 对女

Annual household income was categorized as follows: 100,000–300,000 RMB = 0, less than 100,000 RMB = 1, and more than 300,000 RMB = 2. Health status was defined as unhealthy = 0 and healthy = 1. Body Mass Index (BMI) was classified as normal (< 24.0 kg/m^2) = 0 and overweight/obese (≥ 24.0 kg/m^2) = 1. Smoking status was categorized as never smoked = 0 and former/current smoker = 1, while alcohol consumption was categorized as never drank = 0 and

former/current drinker = 1.

The indirect effect of sleep pattern scores on the risk of diabetes prevalence was significant ($\beta = -0.008, P = 0.004$). When using TyG-BMI and TyG-WC as mediating variables, no significant indirect effects were observed in any of the age-stratified models. These results are detailed in .

2.5 敏感性分析

Physical activity levels were categorized as: no exercise = 0, light exercise = 1, and vigorous exercise = 2. An unweighted four-category sleep score (ranging from 0 to 3, where higher scores indicate better sleep patterns) was utilized as the independent variable. The aforementioned multivariate analysis was repeated, incorporating medical history as covariates, including history of metabolic syndrome (No = 0, Yes = 1) and history of hypertension (No = 0, Yes = 1). Perceived stress levels were categorized as: no stress = 0, manageable stress = 1, and unbearable stress = 2.

2.3 亚组分析与交互作用检验

This study conducted a Logistic regression analysis adjusted for nine covariates, including age, sex, BMI, physical activity, alcohol consumption, smoking status, family history of diabetes, obesity combined with metabolic syndrome, and hypertension. The results were consistent with the primary analysis. After fully adjusting for all potential confounding factors, compared to the reference group with a score of 0 (no sleep problems), individuals with scores of 2 (OR=0.88, 95% CI=0.79-0.98, P=0.020) and 3 (OR=0.83, 95% CI=0.69-0.98, P=0.007) exhibited an increased risk of diabetes prevalence, as shown in Table 7 .

Subgroup analyses and interaction tests were performed across nine covariates: age, sex, BMI, physical activity, alcohol consumption, smoking status, family history of diabetes, obesity combined with metabolic syndrome, and hypertension. After adjusting for the covariates in Model 3 (excluding the stratification variable itself in each respective analysis), the results indicated a significant interaction between age and sleep patterns regarding the risk of diabetes prevalence ($P_{interaction} = 0.019$). Specifically, in individuals aged $\geq$ 60 years, a low-risk sleep pattern was associated with a reduced risk of diabetes (OR=0.78, 95% CI=0.66-0.93); however, this association was not statistically significant in those aged $<$ 60 years. No significant interactions were observed for sex, BMI, physical activity, alcohol consumption, smoking status, family history of diabetes, obesity combined with metabolic syndrome, or hypertension ($P_{interaction} > 0.05$), as detailed in Table 4 .

This study evaluated the association between a composite healthy sleep pattern and the risk of diabetes, while exploring the potential mediating mechanisms of the Triglyceride-Glucose (TyG) index and related obesity indicators. The findings demonstrate that healthier sleep patterns are associated with a lower

risk of diabetes, an association that is more pronounced in individuals aged ≥ 60 years. Furthermore, TyG-BMI and TyG-WC were found to exert mediating effects along this pathway. These findings not only provide robust evidence for sleep as a modifiable risk factor for diabetes but also offer new insights into the "sleep-obesity-metabolic disorder" pathophysiological axis.

2.4 中介作用分析

The chain provides new insights.

3.1 综合睡眠模式与糖尿病风险的关联

In the main effect analysis, this study integrated sleep onset time, subjective sleep quality, and sleep duration to construct a multidimensional weighted sleep score. Using this sleep score as the independent variable and the risk of diabetes as the dependent variable, we constructed three independent mediation models utilizing TyG and TyG-related indices. Compared to previous studies that focused on single sleep dimensions or employed simple "healthy habit counting" methods (which assume equal weights for each dimension), this comprehensive score allows for a more precise quantification of an individual' s overall sleep health.

Note: Model 1 is unadjusted; Model 2 is adjusted for sex, age, education level, and household income; Model 3 further adjusts for diet, BMI, smoking status, alcohol consumption, physical activity, estimated glomerular filtration rate (eGFR), perceived stress level, family history of diabetes, history of metabolic syndrome, and history of hypertension.

Note: The high-risk sleep pattern serves as the reference group.

By weighting the components using logistic regression coefficients, this scoring system objectively reflects the relative contribution of different dimensions to diabetes risk, balancing clinical interpretability with statistical power [**?**]. The results indicate that after adjusting for confounding factors, the low-risk sleep pattern is associated with a lower risk of diabetes (OR = 0.88, 95% CI = 0.80–0.97). This finding is consistent with the general conclusions of previous research [**?**] while providing deeper insights regarding effect size and assessment methodology. Earlier studies often focused on single parameters; for instance, the REACTION study [**?**] reported a "U-shaped" association between sleep duration and type 2 diabetes, while a systematic review [**?**] confirmed that poor sleep quality is correlated with elevated glycated hemoglobin levels. However, these studies failed to evaluate the "cumulative effect" of multiple sleep issues. Other researchers have adopted a "healthy sleep habit counting method" [**?**], but such approaches (i.e., simple binary scoring) often overlook the varying impact of different sleep behaviors.

1 分）假定了各维度（如时长、质量、规律）对糖尿病

The contribution of risks is treated as equivalent, which may not be pathophysiologically accurate. This study confirms the cumulative effect of these independent risk factors through weighting, suggesting that in clinical assessment, the use of multidimensional composite scores may offer superior risk evaluation performance compared to single-dimensional indicators.

This association is supported by a robust biological foundation. On one hand, sleep disturbances can activate the hypothalamic-pituitary-adrenal (HPA) axis and the sympathetic nervous system, leading to increased secretion of stress hormones such as cortisol. This induces chronic inflammatory responses (e.g., elevated levels of tumor necrosis factor-α and interleukin-6), both of which are key drivers of insulin resistance in peripheral tissues [**?**]. On the other hand, insufficient sleep interferes with the secretion of leptin and ghrelin, leading to dysregulation of appetite, promoting central adiposity, and exacerbating the metabolic burden [**?**]. Notably, the independent association between sleep and diabetes remained significant in this study even after controlling for multiple lifestyle factors such as BMI, diet, and physical activity. This suggests that the underlying mechanism is not limited to behavioral pathways but likely possesses an independent physiological regulatory basis.

3.2 年龄的效应修饰作用

Subgroup analysis revealed that the protective association of sleep was more pronounced among individuals aged ≥ 60 years. This finding is consistent with other studies focusing on elderly populations, where the threat of sleep problems to metabolic health has received extensive attention [**?**]. From a pathophysiological perspective, the higher susceptibility observed in the elderly may be attributed to an age-related decline in physiological compensatory capacity, which lowers the threshold for resisting metabolic disorders. Specifically, the aging process is often accompanied by a state of chronic low-grade inflammation and a decrease in basal insulin sensitivity [**?**]. Simultaneously, elderly individuals commonly experience sleep fragmentation (SF). Experimental evidence confirms that SF can independently induce metabolic dysfunction by increasing reactive oxygen species (ROS), promoting adipose tissue inflammation, and downregulating the AMP-activated protein kinase (AMPK) signaling pathway—a core regulator of cellular insulin sensitivity [**?**]. Consequently, the "metabolic shock" induced by sleep fragmentation may exert a synergistic effect with the pre-existing inflammatory and insulin-resistant states in the elderly, thereby more significantly amplifying the negative impact on glucose metabolic homeostasis in this population.

The "metabolic shock" induced by sleep fragmentation may exert a synergistic effect with the pre-existing inflammatory and insulin-resistant states in the elderly, thereby more significantly amplifying the negative impact on glucose metabolic homeostasis in this population.

This finding carries significant public health implications, highlighting that improving sleep health may be a critical and cost-effective strategy for diabetes prevention specifically targeted at the elderly. Future interventions should fully account for age-related heterogeneity to implement precise health management.

3.3 中介机制：肥胖相关胰岛素抵抗及性别差异

The mediation analysis in this study provides direct epidemiological evidence for the classic interaction pathway of "sleep-obesity-insulin resistance." A significant finding of this research is that the Triglyceride-Glucose (TyG) index alone—which reflects only glucose and lipid metabolism—does not serve as a mediating factor between sleep scores and diabetes risk. Conversely, when the TyG index is combined with obesity indicators such as Body Mass Index (BMI) or Waist Circumference (WC), the mediating effect becomes significant. This result strongly supports the hypothesis that "obesity is the critical bridge connecting sleep disturbances to metabolic abnormalities." These findings suggest that poor sleep may not lead to glucose and lipid metabolism disorders in a direct or isolated manner; rather, it primarily influences body fat distribution and accumulation, which subsequently triggers systemic insulin resistance and increases the risk of diabetes.

Table 7: Dose-Response Relationship between Sleep Score and the Risk of Diabetes

Variable	Model 1 OR (95% CI)	Model 2 OR (95% CI)	Model 3 OR (95% CI)
Sleep Score (Continuous)	1.18 (1.09–1.27)	1.19 (1.08–1.30)	1.16 (0.99–1.36)
P-value	<0.001	<0.001	0.062
Low Sleep Score	0.96 (0.88–1.04)	0.90 (0.81–0.99)	0.84 (0.71–0.99)
High Sleep Score	0.95 (0.88–1.04)	0.88 (0.79–0.98)	0.83 (0.69–0.98)

Note: - **Model 1:** Unadjusted. - **Model 2:** Adjusted for sex, age, education level, and income level. - **Model 3:** Adjusted for the variables in Model 2 plus dietary habits, BMI, smoking status, alcohol consumption, physical activity, estimated glomerular filtration rate (eGFR), self-reported stress levels, family history of diabetes, history of metabolic syndrome, and history of hypertension.

[Figure 1: see original paper] Figure 1. Path diagrams for the mediating effects of TyG, TyG-WC, and TyG-BMI on the association between weighted sleep score and diabetes.

Discussion

Neuroendocrine and inflammatory regulation pathways promote the abnormal accumulation of adipose tissue, which subsequently leads to severe insulin resis-

tance mediated by obesity, ultimately resulting in the development of diabetes. Furthermore, this study analyzed insulin resistance related to different obesity phenotypes.

There are several limitations to this study. First, the study population may exclude individuals with "impaired glucose tolerance" due to the lack of Oral Glucose Tolerance Test (OGTT) data. Second, information regarding "medication use" —specifically sedative-hypnotics and hormonal drugs—was not systematically collected. These unmeasured confounding factors may have an impact on the observed results.

Resistance was differentiated. The results indicated that while both TyG-BMI (representing general obesity, indirect effect $P = 0.017$) and TyG-WC (representing central obesity, indirect effect $P = 0.044$) served as mediating factors, TyG-BMI exhibited a larger effect size. This finding warrants further exploration, as it suggests that the metabolic consequences arising from poor sleep may be more closely linked to general adiposity. Future research should focus on more comprehensive data collection to enhance the reliability and external validity of these conclusions.

The systemic increase in body fat caused by specific patterns may play an earlier or more potent mediating role in the pathological pathways triggering insulin resistance than central adiposity alone. This hypothesis warrants further verification in future studies using more precise body composition measurements. Furthermore, the heterogeneity analysis in this study revealed gender-specific characteristics in the mediating pathway of the TyG index. We observed a significant moderating effect of gender on the TyG mediation pathway ($P_{interaction} = 0.028$), with the indirect effect being more pronounced in women.

This phenomenon may be rooted in fundamental differences between the sexes regarding fat distribution patterns and metabolic regulation [**?**]. Under metabolic stress, such as sleep deprivation or disturbance, men are more prone to accumulating visceral fat. Visceral fat acts as a highly pro-inflammatory organ that drives insulin resistance through potent pathways such as chronic inflammation [**?**]. This robust pathophysiological mechanism may overshadow the specific glucose and lipid metabolism pathways represented by the TyG index in men. In contrast, women are often protected by estrogen and tend to store fat subcutaneously [**?**]. Lacking the dominant "visceral fat-inflammation" pathway seen in men, the metabolic benefits of improved sleep may be more readily observed through the modulation of insulin resistance markers in women.

In conclusion, the results of this study indicate that a healthier composite sleep pattern is associated with a lower risk of diabetes prevalence, an association that is particularly prominent among the elderly. Obesity-related insulin resistance indicators (TyG-BMI and TyG-WC) play a partial mediating role in this association, suggesting that good sleep may reduce diabetes risk by improving obesity-related insulin resistance. Future research should further verify

these causal relationships through prospective cohorts and intervention trials, while exploring more actionable sleep improvement strategies to aid in the early prevention and control of diabetes.

Author Contributions:

Liu Xiaowu was responsible for data organization, manuscript drafting, statistical analysis, conceptualization, and study design, and serves as the guarantor for the overall integrity of the article. Tang Ningbin participated in data organization and preliminary analysis. Lin Mi contributed to data organization. Lu Taoying participated in data collection. Cai Jianxiong was involved in manuscript drafting and revision. Liu Wofeng and Zhong Yuping were responsible for data collection and laboratory sample processing. Zeng Hongli performed data collection, data quality control, and manuscript review. Wu Darong was responsible for quality control, monitoring of statistical methods, and final review of the manuscript.

The activation of the hypothalamic-pituitary-adrenal (HPA) axis and subsequent elevation of cortisol levels lead to increases in blood glucose and triglycerides [**?**]. This mechanism may constitute a more detectable pathological pathway within the female population. Because the Triglyceride-Glucose (TyG) index specifically captures this pathway, its mediating role is more prominent in women. These findings suggest that future interventions may need to account for distinct, gender-based pathophysiological pathways.

3.4 本研究的优势、创新性与局限性

A primary strength of this study lies in the construction of a data-driven weighted sleep score, which accounts for the varying weights of different sleep habits in their contribution to diabetes, thereby allowing for a more precise quantification of composite sleep patterns. Furthermore, this study systematically compares the mediating roles of the Triglyceride-Glucose (TyG) index, TyG-BMI, and TyG-WC in the association between sleep and diabetes. The authors declare no conflicts of interest.

Xiaowu Liu https://orcid.org/0000-0002-1285-0622; Darong Wu https://orcid.org/0000-0003-3159-7359. [**?**] ONG K L, STAFFORD L K, MCLAUGHLIN S A, et al. Global, regional, and national burden of diabetes from 1990 to 2021, with projections of prevalence to 2050: a systematic analysis for the Global Burden of Disease Study 2021[J]. Lancet, 2023, 402(10397): 203-234. DOI: 10.1016/S0140-6736(23)01301-6. [**?**] LYSSENKO V, VAAG A. Genetics of diabetes-associated microvascular complications[J]. Diabetologia, 2023, 66(9): 1601-1614. These findings provide new clues for understanding the underlying pathophysiological mechanisms. Nevertheless, this study has certain limitations. First, the study employs a cross-sectional design, which precludes the establishment of causal relationships.

1613. DOI: 10.1007/s00125-023-05964-x.

First, the cross-sectional design of this study precludes the exploration of causal relationships. Second, this is a single-center study with participants recruited exclusively from the Guangzhou area; the specific regional characteristics may limit the generalizability of our findings to the broader national population. Furthermore, sleep behavior data—including duration, quality, and sleep onset time—were based on self-reports rather than objective measurements such as polysomnography, which may introduce recall bias and measurement error.

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Additionally, this study utilized subjective sleep onset time as a proxy for sleep phase but did not incorporate "wake-up time," which prevented a comprehensive assessment of "sleep regularity." Information regarding sleep-disordered breathing, such as snoring, was also not systematically collected. Finally, although we adjusted for several confounding variables—including family history of diabetes, estimated glomerular filtration rate (eGFR), and perceived stress levels —the possibility of residual confounding remains. For instance, we were unable to accurately identify "prediabetes" or other subclinical metabolic states that might influence the observed associations.

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Note: Figure translations are in progress. See original paper for figures.