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Sleep and eating patterns in individuals with gestational diabetes: associations with daily overnight and morning glucose using continuous glucose monitoring☆

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ABSTRACT

Background and aims: The influence of diet and sleep and their combined effect on daily glucose control in individuals with gestational diabetes mellitus (GDM) remains unclear. This study investigated real-time associations between eating and sleep patterns with overnight and morning glucose using ecological momentary assessment.

Materials and methods: Thirty-four untreated patients with GDM wore a continuous glucose monitoring at 28 ± 2 weeks of gestation for 6 days; data from the first day were excluded. Five-day average and daily measures of overnight mean glucose, variability (SD), glycemic area under the curve (AUC), and glucose upon waking were calculated. Predictors included daily food diaries, sleep questionnaires, and sensor day. Multivariate stepwise regressions identified key predictors, and ANOVAs assessed temporal differences in glucose outcomes.

Results: Participants were 34 ± 6 years old with a pre-pregnancy BMI of 28 ± 6 kg/m^2. Greater day-to-day variability in snack intake was associated with increased 5-day average overnight mean glucose and AUC ($p \leq 0.03$). Later dinner was associated with greater overnight glucose variability ($p \leq 0.01$). Sleep parameters were not associated with glucose outcomes. Glucose measures differed significantly across days ($p \leq 0.03$).

Conclusion: Daily variations in overnight and morning glucose should be considered. Irregular snacking and delayed meal timing could disrupt circadian glucose regulation; promoting consistent and earlier evening meals could support improved nocturnal glycemic control in patients with GDM.

1. Introduction

Gestational Diabetes Mellitus (GDM) is any degree of glucose intolerance first diagnosed during pregnancy which does not fulfil the criteria of overt diabetes.[1] Affecting approximately 14% of pregnancies worldwide,[2] GDM increases short- and long-term health risks for mothers and their offspring, including type 2 diabetes mellitus (T2DM), obesity, and cardiovascular risk.[3] Poor glycemic control is linked to a more pronounced risk of neonatal complications and of future T2DM.[4,5] Notably, elevated overnight glucose in women with GDM have been associated with large for gestational age infants.[6] This underscores the importance of optimizing glycemic control during pregnancy.

In clinical practice, fasting morning glucose levels vary among patients with GDM when using capillary or continuous glucose monitoring (CGM). CGM captures short-term fluctuations not detected by more traditional methods. However, some of its variability may reflect measurement errors, including improper placement of sensor, site compression, or timing of sensor insertion. Accuracy may be reduced during the first 12–24 h due to local inflammation after insertion.[7,8] While CGM offers clear benefits in type 1 diabetes mellitus (T1DM)

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during pregnancy, more data regarding clinical care in GDM is needed.[9]

Modifiable lifestyle factors, including eating behaviors and sleep, can influence overnight and morning glucose variability. During pregnancy, sleep is commonly disrupted by hormonal, anatomical, and physical discomfort.[10] Approximately 45% of pregnant women report poor sleep quality,[11] with even worse quality among individuals with GDM.[12] Shorter sleep duration in the second trimester has been associated with impaired glucose metabolism during an oral glucose tolerance test (OGTT).[13] Outside of pregnancy, poor sleep quality is linked to impaired glycemic control and increased glycemic variability in adults with T1DM and T2DM.[14,15]

Eating patterns commonly refer to the timing, duration, and frequency of food intake across the day.[16] In pregnancy and postpartum, nocturnal eating behaviors, including late evening meals, have been associated with elevated fasting glucose levels and HbA1c.[17–19] Irregular meal patterns have also been linked to reduced insulin sensitivity in both lean and women with obesity.[20,21] Evening meal timing plays a key role in glucose control in individuals with diabetes,[22] particularly in the context of nocturnal eating.[23] Thus, sleep and eating patterns and their regularity may influence overall glycemic control and day-to-day glucose variability in patients with GDM, but remain understudied.

While prior studies have investigated the associations between sleep or eating patterns and glucose metabolism during pregnancy, these factors have been studied separately and often using single-time-point assessments (e.g., fasting glucose or oral glucose tolerance test results). However, the combined effects of sleep and eating patterns and their day-to-day influence on continuous overnight and morning glucose levels using CGM in untreated patients with GDM remain unknown, a critical period when lifestyle behaviors may strongly influence glycemic regulation.[13,17–19] To address these gaps, we 1) investigated the associations between 5-day mean and variability of eating patterns and sleep with averaged overnight and morning blood glucose levels, and 2) examined whether days after sensor insertion, as well as daily eating patterns and sleep, predict daily values of overnight and glucose levels upon waking. By integrating ecological momentary assessments with CGM, this study captures real time associations of sleep and eating patterns with overnight glucose in patients with GDM, providing new insights into how these behaviors jointly contribute to glycemic variability on daily life. Understanding these lifestyle factors and their combined effects on overnight and morning glucose could guide dietary and sleep interventions to improve maternal and neonatal outcomes for patients with GDM.

2. Subjects

2.1. Participant consent and recruitment

This study is a prospective observational study with repeated daily measures. It is part of an ongoing longitudinal cohort of individuals diagnosed with GDM (a glucose intolerance diagnosed during pregnancy, not fulfilling the criteria of overt diabetes[1]). GDM was diagnosed in accordance with the International Association of the Diabetes and Pregnancy Study Groups and consistent with the American Diabetes Association guidelines (fasting plasma glucose ≥5.1 mmol/L, 1 h glucose ≥10.0 mmol/L, or 2 h glucose ≥8.5 mmol/L based on a 2 h 75 g oral glucose tolerance test).[24,25] After diagnosis, patients were followed by a physician or a diabetes-specialist nurse, and by a registered dietician for individualized dietary advice and gestational weight gain counseling based on the recommendations of the National Academy of Medicine.[26] Current dietary recommendations in our clinic emphasize on optimizing carbohydrate quality and quantity (around 175 g per day distributed across 3 meals and additional snacks based on personal needs), favoring low- to moderate- glycemic index carbohydrates and sufficient soluble fiber intake.[27–29]

Eligible patients receiving antenatal follow-up care at the GDM Unit at the Lausanne University Hospital, Switzerland, were invited to participate and all participating patients signed informed consent. The Human Research Ethics Committee of the Canton de Vaud, Switzerland, approved the study protocol (326/15).

2.2. Inclusion and exclusion criteria

Participants were eligible if they were adults followed in our clinic between February 2020 and December 2023, had at least two fasting capillary glucose readings >5.3 mmol/L within 7 days, and clinicians deemed it safe to delay treatment. Other criteria included fluency in English, French, or Spanish, and no current use of glucose-lowering medications or other drugs affecting glucose metabolism.

Eligible participants were invited to participate. Those who consented were enrolled through convenience sampling technique. Given the exploratory nature of this study, no formal sample size calculation was performed. Of 45 participants who provided informed consent, data were excluded for those who dropped out ($N = 2$), did not complete any days of the sleep questionnaire or food dairy ($N = 3$), had no CGM data (N = 2), had only 2 days of CGM data (N = 2), or had mismatched dates between questionnaires and CGM data (N = 2). The final analysis included 34 participants.

3. Material and methods

3.1. Study design

Upon participation agreement, healthcare providers (O.L.D., M.T.M.) inserted the Dexcom G6® CGM on the participants' upper arm and provided detailed instructions for proper use according to the manufacturer's guidelines. Ecological momentary assessment (EMA) is a method of longitudinal assessments of various factors during daily activities.[30] As part of the EMA, participants completed a sleep questionnaire each morning upon waking and recorded all meals and snacks consumed between 18 h and wake-up time in a paper-and-pen food diary. Participants were offered the option to send pictures of their meals or snacks prior to consumption. After one week, participants returned the CGM reader and completed set of questionnaires for analysis.

To investigate both study aims, predictors included reported daily eating pattern variables (total number of snacks, dinner time, and time of last food intake) and sleep patterns (bedtime, number of nighttime awakenings, sleep duration, and sleep quality). The outcomes in this study included overnight mean glucose levels, standard deviation of overnight glucose levels, area under the curve of overnight glucose levels, and glucose levels upon waking using CGM.

3.2. Sociodemographic and anthropometric measures

Maternal age, nationality, and educational level were collected during the first GDM visit, between 24 and 32 weeks of gestation. Additionally, we recorded the gestational age at the first GDM visit, prior history of GDM, parity, gravida, pre-pregnancy BMI (in kg/m^2), gestational weight gain at 1st visit (calculated as the measured weight at 1st visit – medical chart-based pre-pregnancy weight, kg). Data on need for insulin treatment during pregnancy after study participation were extracted from participant medical charts. Height (cm) and weight (kg) were measured using an electronic scale (Seca®).

3.3. Assessment of glycemic measurements

Glycemic levels were monitored for 6 days using Dexcom G6® CGM, with measurements every ~5 min. This study focused on two timeframes: overnight (00:00 to 06:00), commonly used timeframe to approximate sleep in CGM analyses,[31] and a self-reported wake-up time to capture glucose levels upon waking.

Raw CGM data were aligned to a fixed 5-minute grid spanning 72

time points. Each measurement was assigned to the nearest preceding 5-minute mark, and multiple readings within the same interval were averaged. Grid averaging was used instead of rounding, as measurement intervals vary, and rounding could increase missing values. Overnight periods >30% missing data were excluded. Artefacts (≤ 2.2 mmol/L in untreated patients) and large drops (>35% between two consecutive 5-min values, as indicated by the manufacturer) were removed. The first day of sensor wear was excluded from analyses, due to potential local inflammation affecting accuracy during the first 12–24 h.[7,8]

Key metrics included overnight mean glucose, standard deviation (SD), and total glycemic exposure during the night measured as the overnight glucose area under the curve (AUC). Additionally, daily glucose level at self-reported wake-up was obtained.

3.4. Assessments of eating and sleep patterns

Eating patterns were assessed using a paper-and-pen detailed food diary where participants recorded detailed information on all meals and snacks consumed between 18 h and wake-up time. Participants were also given the option to submit pictures of their meals and snacks before consumption. A dietitian analyzed the collected dietary records, including the total number of snacks, the timing of dinner and of the last carbohydrate intake (HH:MM).

Sleep quality was assessed each night using the clinically accepted six-item Spiegel Sleep Questionnaire.[32] The questionnaire evaluates sleep initiation, quality, duration, disruptions, dream recall, and morning wakefulness. Items are scored on a 5-point Likert scale (total: 0 to 30 points), with higher scores indicating better sleep quality. Participants completed the questionnaire each morning for the preceding night and additionally recorded their bedtime, wake-up time, and the number of nighttime awakenings.

3.5. Statistical analysis

All statistical analyses were conducted in R v4.4.2 running on RStudio 2024.09.1 build 394.[33] Statistical methods were selected to address the two study objectives: 1) to examine associations between mean and day-to-day variability in eating and sleep patterns with averaged overnight and morning glucose levels, and 2) to assess within-person, day-to-day associations between these behaviors and glucose measurements over time.

Statistical analyses focused on overnight period (00:00 to 06:00), as this window is a recommended timeframe to approximate sleep in CGM analysis.[31] Morning glucose levels were extracted from CGM data at each participant's self-reported wake-up time. Summary and glycemic variability metrics were calculated using the rGV[34] and iglu[35] R packages following artifact removal (see above). To reduce potential bias due to local inflammation, sensor calibration, and adaptation,[7] the first day of CGM data was excluded, and thus all analyses were conducted using data from days 2 to 6. For each participant, daily mean values of glucose, eating, and sleep variables were calculated for each of the 5 days.

3.5.1. Objective 1

The daily mean values of glucose, eating, and sleep variables were then averaged to obtain an overall mean for the 5-day period for each participant. The day-to-day variability of the predictors was quantified as the standard deviation of daily values across the 5 days, reflecting intra-individual behavioral variability. This approach allows us to differentiate associations driven by mean behavioral patterns and those driven by variability over time. To study the associations between mean and day-to-day variability in eating and sleep patterns with averaged overnight and morning glucose levels, we used linear regressions with stepwise variables selection.

3.5.2. Objective 2

To investigate associations between eating and sleep patterns with glucose metrics, two stepwise linear regression models were conducted: (1) The first model assessed whether mean eating and sleep patterns were associated with mean glucose measurements; (2) The second model assessed whether day-to-day variability in eating or sleep patterns was associated with 5-day mean glucose measurements.

To investigate associations between eating and sleep patterns with glucose metrics, we conducted univariate and multivariate linear mixed-effects models with random intercepts that were then fitted using stepwise selection to account for repeated measures and identify optimal variable combinations. Four model sets were analyzed: with/without effect of time, and with/without the adjustment for sociodemographic and medical confounders (age, gestational age at 1st visit, pre-pregnancy BMI, family history of diabetes, gestational weight gain at 1st visit, and history of GDM). As results were consistent across model specifications, only the fully adjusted model including effect of time and confounders is presented in the Results.

To examine temporal effects on glucose measurements and account for the repeated-measures structure of the data, linear mixed-effects models with random intercepts for participants were conducted. Type III ANOVA was used to evaluate fixed effects, and Post hoc pairwise comparisons were conducted using estimated marginal means.

3.6. Statistical approach

Linear regression models were used for 5-day averaged outcomes, while linear mixed-effects models with random intercepts were applied to account for repeated daily measurements within participants.

Prior to model fitting, potential multicollinearity among predictors was assessed using the variance inflation factor (VIF >10) to identify highly correlated predictors for exclusion, ensuring model stability.[36]

The predictors included in the initial model were total number of snacks, dinner time, time of last food intake, bedtime, number of nighttime awakenings, sleep quality measured with the Spiegel Sleep Questionnaire score and sleep duration. Stepwise variable selection was used given the exploratory nature of the study, the limited sample size, and the number of correlated behavioral predictors, with the aim of identifying the most relevant contributors to glycemic outcomes. Covariates were selected a priori based on clinical relevance and prior literature.

Model assumptions were assessed to ensure the validity of the linear and mixed-effects models. Linear regression assumptions were checked using residual diagnostics, multicollinearity among predictors was assessed via VIF, and normality of residuals was tested with the Shapiro-Wilk test. When tests yielded non-normal residuals (Shapiro-Wilk $p < 0.05$), log transformations on outcomes were applied. For the outcome AUC, residuals remained non-normally distributed after transformation; consequently, these data were therefore excluded from the multivariate linear mixed-effects model analysis.

The effect sizes were quantified using eta-squared (η^2) with small effect ≥0.01; medium effect ≥0.06 and large effect ≥0.14.[37] Marginal and conditional coefficients of determination were calculated for generalized mixed-effects models to estimate the variance explained by fixed-effects compared to the full model, including both fixed and random-effects. Coefficient of determination (R^2) and partial R^2 values were used to estimate the proportion of outcome variation explained by the models and individual predictors. All statistical tests were two-tailed with a significance level of $\alpha < 0.05$. All statistical analyses were conducted in R v4.4.2 running on RStudio 2024.09.1 build 394.[33]

Key analytical decisions, including exclusion of the first CGM day, handling of missing CGM data, artifact removal, variable transformations, and model diagnostics, were prespecified and are described to enhance reproducibility in future studies using similar CGM and ecological momentary assessment designs.

4. Results

4.1. Descriptive medical characteristics of study participants

The final sample was composed of 34 participants. The mean age of the study participants was 34 ± 6 years and their mean gestational age was 28 ± 2 weeks (Table 1). Participants had a pre-pregnancy BMI of 28.1 ± 6.0 kg/m^2. Seventy-nine percent of participants reported a family history of diabetes and 24% had a previous history of GDM.

4.2. Eating patterns, sleep, and glycemic levels of participants

Table 2 shows the mean ± SD of participants' eating and sleep patterns, and blood glucose levels. On average, participants ate their dinner at 19:50 h ± 01:13 h and had their last food intake at 20:48 h ± 02:04 h. They went to bed at a mean time of 23:14 h ± 01:31 h and slept for an average of 8 ± 2 h and reported a sleep quality score of 21 ± 4.

During the night, the average mean glucose level was 5.9 ± 0.9 mmol/L and the mean fasting blood glucose level upon waking was 5.6 ± 1.0 mmol/L.

4.3. Associations of 5-day average eating and sleep patterns with 5-day mean glucose measurements

The full models including mean sleep and eating patterns explained 9–24% of the variance in average glucose measurements (Table 3A), but only the model predicting the SD of overnight glucose reached statistical significance. The only individual sleep or eating measure associated with glucose measurements was dinner time: It correlated with SD of overnight glucose ($\beta = 0.11$, $p = 0.01$, $\eta^2 = 0.23$) and uniquely accounted for 23% of the 5-day average overnight glucose variability (partial $R^2 = 0.23$). No associations were observed with sleep measures.

Table 1
Demographic and medical characteristics of study participants ($n = 34$).

Variables	Frequency (%)
Age (years) (mean ± SD)	33.8 ± 5.6
GA at first GDM visit (weeks) (mean ± SD)	28 ± 1.5
Pre-pregnancy BMI (kg/m^2) (mean ± SD)	28.1 ± 6.0
Gestational weight gain at 1st visit (kg) (mean ± SD)	8.5 ± 5.9
Nationality/ethnic origin	
Switzerland	12 (35.3)
Europe & North America	9 (26.5)
Asia & Oceania	7 (20.6)
Latin America	4 (11.8)
Africa	2 (5.9)
Family history of diabetes	
No	7 (21.2)
1st degree	12 (36.4)
2nd degree	14 (42.4)
Educational status	
Compulsory school achieved	3 (15)
High school	3 (15)
General and vocational education	4 (20)
University	10 (50)
Gravida	
1	14 (41.2)
2	4 (11.8)
≥3	16 (47.1)
Parity	
0	18 (52.9)
1	10 (29.4)
2	6 (17.6)
Previous history of GDM	
No	11 (33.3)
Not applicable (Primigravida)	14 (42.4)
Yes	8 (24.2)
Need for insulin treatment during pregnancy[a], yes	22 (64.7)

Notes: GA: gestational age; GDM: gestational diabetes mellitus; BMI: body mass index.
[a] Following study participation.

Table 2
Eating and sleep patterns, and glycemic levels of participants (n = 34).

Measurements	Total number of observations	Mean ± SD
Eating		
Total number of snacks	173	0.7 ± 0.8
Dinner time (HH:MM)	183	19:50 ± 01:13
Time of last food intake (HH:MM)	186	20:48 ± 02:04
Sleep		
Bedtime (HH:MM)	191	23:14 ± 01:31
Number of nighttime awakenings	190	2.4 ± 1.9
The Spiegel Sleep Questionnaire score[a]	194	21 ± 4
Sleep duration (HH:MM)	183	07:44 ± 02:02
Wake-up (HH:MM)	183	06:40 ± 04:10
Glucose		
Overnight mean glucose levels (mmol/L)[b]	180	5.9 ± 0.9
Standard deviation of overnight glucose levels (mmol/L)[b]	180	0.6 ± 0.3
Area under the curve of overnight glucose levels (mmol/L*h)[b]	180	182.1 ± 155.5
Glucose levels upon waking (mmol/L)[c]	180	5.6 ± 1.0

[a] Possible score range from 0 to 30 points, with higher scores indicating better sleep.
[b] Overnight values measured between 00:00 and 06:00.
[c] Measurement taken at the reported wake-up time.

4.4. Associations of day-to-day variability in eating and sleep patterns with 5-day mean glucose measurements

The full models including day-to-day variability of sleep and eating patterns over 5 days explained 13–40% percent of the variance in mean glucose measurements (Table 3B). The full models for overnight mean blood glucose levels, AUC, and glucose level upon waking showed trends toward significance. Similar to Table 3A, only the individual variability of the total number of snacks was associated with both overnight glucose levels ($\beta = 1.17$, $\eta^2 = 0.32$, $p = 0.02$) and AUC ($\beta = 170.94$, $\eta^2 = 0.2$, $p = 0.03$), and uniquely accounted for 26% and 20% of the variability of the outcomes, respectively (partial $R^2 = 0.26$ and 0.20, respectively). No associations were observed with sleep measures.

4.5. Effect of time on glucose measurements

There were overall differences across days for overnight mean glucose levels ($X^2(4) = 28.73$, $p < 0.001$), overnight area under the curve (AUC) ($X^2(4) = 12.65$, $p = 0.01$), and glucose levels upon waking ($X^2(4) = 11.16$, $p = 0.03$), but not for the standard deviation of overnight glucose levels (Fig. 1). For both glucose levels upon waking and AUC, post hoc comparisons showed differences between day 2 and day 6, and for overnight mean glucose levels between day 2 and day 4, 5 and 6.

4.6. Daily effects of eating and sleep patterns on glucose measurements

Within-person changes in glucose measurements over time were assessed in relation to eating and sleep patterns, adjusting for the effect of time and key confounders (Table 4). No eating or sleep patterns predicted mean overnight or waking glucose levels, whereas time (days) had a significant effect. In contrast, dinner time predicted the overnight glucose variability (SD). More specifically, each hour delay in dinner time was associated with a 17% increase in overnight glucose variability (multiplicative factor: $\beta = 1.17$, $p = 0.001$, $\eta^2 = 0.13$) in adjusted analyses. No associations were observed with sleep measures.

Table 3
Associations of eating and sleep patterns and 5-day average glucose measurements.

Average values of:	F test	Actual power	R^2	Predictors[(1)]	Partial R^2	Estimate [95% CI]	*p* value	η^2
A. 5-day average eating and sleep patterns and glucose measurements								
Overnight mean blood glucose levels (mmol/L)	F(2,24) = 2.12, p = 0.14	0.43	0.15	Total number of snacks	0.08	0.31 [−0.12, 0.73]	0.17	0.08
				Dinner time	0.09	0.23 [−0.05, 0.51]	0.13	0.09
Standard deviation of overnight glucose levels (mmol/L)	**F(2,24) = 3.81, p = 0.04**	0.69	0.241	Sleep duration	0.10	0.04 [−0.01, 0.08]	0.13	0.02
				Dinner time	**0.23**	**0.11 [0.03, 0.20]**	**0.01***	0.23
Area under the curve of overnight glucose levels (mmol/L*h)	F(1,25) = 2.56, p = 0.12	0.36	0.093	Dinner time	0.09	41.45 [−9.32, 92.22]	0.12	0.09
Glucose levels upon waking (mmol/L)	NS[a]			NS[a]				
B: 5-day variability in eating and sleep patterns and glucose measurements								
Overnight mean blood glucose levels (mmol/L)	F(5,20) = 2.67, p = 0.05	0.82	0.40	**Total number of snacks**	0.26	1.17 [0.29, 2.04]	**0.02***	0.32
				Bedtime	0.08	−0.33 [−0.81, 0.16]	0.2	0.04
				Time of last food intake	0.08	0.33 [−0.18, 0.83]	0.22	0.08
				Number of nighttime awakenings	0.11	0.30 [−0.07, 0.66]	0.13	0.05
				Sleep quality	0.18	−0.29 [−0.56, −0.02]	0.05	0.01
Standard deviation of overnight glucose levels (mmol/L)	F(2,23) = 1.88, p = 0.18	0.39	0.14	Number of nighttime awakenings	0.08	0.08 [−0.03, 0.19]	0.18	0.01
				Sleep quality	0.14	−0.07 [−0.15, 0.002]	0.07	0.14
Area under the curve of overnight glucose levels (mmol/L*h)	F(3,22) = 2.56, p = 0.08	0.63	0.26	**Total number of snacks**	0.20	170.94 [27.67, 314.20]	**0.03***	0.20
				Number of nighttime awakenings	0.12	56.65 [−9.02, 122.31]	0.11	0.04
				Sleep quality	0.15	−46.11 [−92.81, 0.59]	0.07	0.05
Glucose levels upon waking (mmol/L)	F(1,23) = 3.55, p = 0.07	0.47	0.13	Total number of snacks	0.13	0.81 [−0.03, 1.65]	0.07	0.13

Notes: Generalized linear model (1) the predictors were selected with a stepwise approach. Predictors included in the initial model: total number of snacks, dinner time, time of last food intake, bedtime, number of nighttime awakenings, sleep quality measured with the Spiegel Sleep Questionnaire score and sleep duration.

[a] NS: No predictors were significant to be included in the model.

[*] Values in bold with an asterisk indicate statistical significance ($p<0.05$).

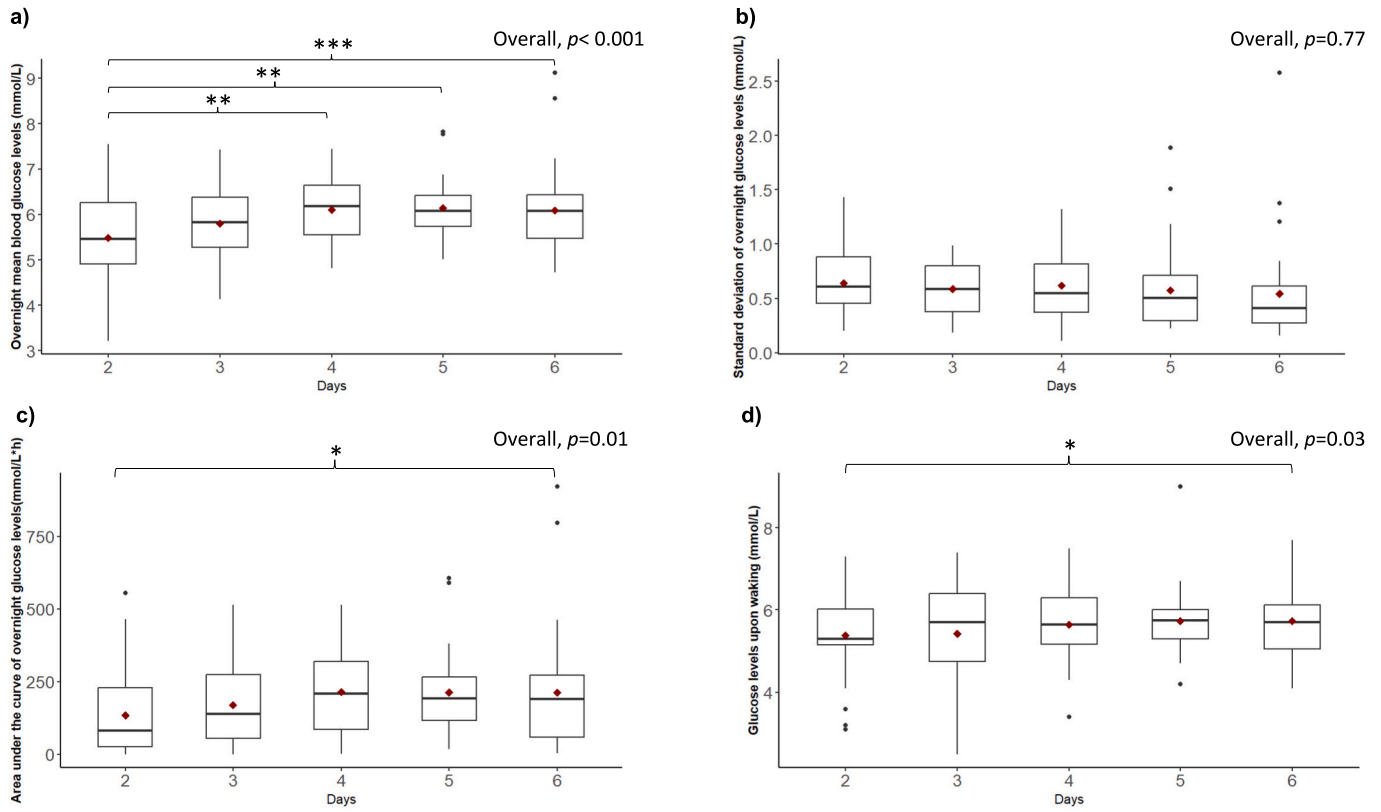

Fig. 1. Main effect of time on daily values of glucose measurements.
Notes: Overall temporal differences were evaluated using ANOVA. Analyses summarize both overall and pairwise day-to-day differences for each glucose measurement. Significant differences were observed for overnight mean blood glucose levels (day 2 vs. days 4, 5, and 6), overnight glucose area under the curve (day 2 vs. day 6), and glucose levels upon waking (day 2 vs. day 6). Pairwise significance levels are indicated as follows: $*p < 0.05$, $**p < 0.01$, $***p < 0.001$.

Table 4
Effects of multiple predictors and time on daily values of glucose measurements.

Daily values of:	Predictor(1)	n/obs	R^2m/R^2c	Estimate [95% CI]	*Multiplicative effect* [95% CI]	*p* value	η^2
Overnight mean blood glucose levels *(mmol/L)*	(Intercept – Day 2)	25 /99	0.37 / 0.53	5.84 [3.58, 8.10]	*NA*	**<0.001**	0.17
	Day 3			0.29 [3.58, 8.10]	*NA*	0.18	
	Day 4			0.51 [0.10, 0.92]	*NA*	0.02	
	Day 5			0.70 [0.28, 1.12]	*NA*	0.002	
	Day 6			0.72 [0.28, 1.16]	*NA*	0.002	
	Age			−0.06 [−0.10, −0.03]	*NA*	0.01	0.34
	Pre-pregnancy BMI			0.05 [0.01, 0.10]	*NA*	0.04	0.19
	GWG at 1st visit			0.04 [0.004, 0.07]	*NA*	0.04	0.19
Overnight standard deviation of glucose levels# *(mmol/L)*	(Intercept – Day 2)	25/99	0.12 / 0.35	−3.78 [−5.60, −1.97]	0.02 [0.004, 014]	<0.001	
	Dinner time			**0.16 [0.07, 0.25]**	**1.17 [1.07, 1.28]**	**0.001**	**0.13**
Glucose levels upon waking *(mmol/L)*	(Intercept – Day 2)	24/94	0.23 / 0.58	7.48 [5.69, 9.27]	*NA*	<0.001	0.21
	Day 3			0.24 [−0.18, 0.67]	*NA*	0.26	
	Day 4			0.51 [0.09, 0.92]	*NA*	0.02	
	Day 5			0.71 [0.28, 1.14]	*NA*	0.002	
	Day 6			0.83 [0.39, 1.27]	*NA*	<0.001	
	Age			−0.07 [−0.12, −0.02]	*NA*	0.02	0.24

Notes: (1) the predictors were selected using a stepwise approach. Predictors included in the initial model: total number of snacks, dinner time, time of last food intake, bedtime, number of nighttime awakenings, sleep quality measured with the Spiegel Sleep Questionnaire score and sleep duration. The tested covariates included in the initial model: age, gestational age at 1st visit, pre-pregnancy BMI, family history of diabetes, gestational weight gain at 1st visit, and previous history of GDM. N: number of patients; OBS: number of observations; NA: not applicable; η^2: Eta-squared (effect size); #: Outcome was log-transformed prior to analysis; estimate is presented on the ln scale and exponentiated to obtain the multiplicative effect.

5. Discussion

In individuals with GDM, mean values and day-to-day variability of combined eating and sleep patterns, including food timing, number of snacks, sleep duration, bedtime, nighttime awakenings, and sleep quality explained up to 40% of the variance in 5-day average glucose measurements, though most models did not reach significance. Among individual measures, only dinner time and variability in the number of snacks were related to 5-day average glucose measurements. Across days, time was the strongest contributor to daily values of overnight and

morning glucose levels. Later dinner time was the only independent predictor of higher day-to-day overnight and waking glucose and was associated with increased daily variability in overnight glucose levels.

A later mean dinner time and a greater day-to-day variability in the number of snacks over 5 days were associated with higher overnight mean glucose levels, variability, or AUC. Previous studies in healthy pregnant individuals have shown that late evening eating and shorter nocturnal fasting intervals are associated with higher glucose values,[17,18] and our data extend this evidence to individuals with GDM. Crossover trails outside pregnancy suggest that regular meal frequency improves insulin sensitivity in women, both lean[20] and with obesity.[21] One possible explanation is that eating at a later time may interact with circadian regulation of glucose metabolism and insulin secretion. Studies suggest that eating meals at times misaligned with internal clocks can cause circadian desynchrony and increase insulin resistance.[38–40] Additionally, solid-phase gastric emptying is slower for meals consumed in the evening.[41] Hypothetically, this slower emptying could contribute to higher or more variable overnight glucose levels. Consuming >25% of daily intake after dinner has been associated with elevated HbA1c levels and increased risk of diabetes complications.[23] The impact of dietary timing in GDM remains poorly understood. These effects are often confounded by recall bias, reducing dietary assessment accuracy and limiting practical recommendations. To address this, we prospectively collected daily CGM, eating, and sleep data under free-living conditions, allowing a more comprehensive evaluation of glucose dynamics in everyday life.

Within-person changes over 5 days indicated that a later dinner time was associated with increased overnight glucose variability, independent of the effect of time and key confounders. Each one-hour delay in dinner time corresponded to a 17% increase in daily overnight glucose variability. Similar day-to-day analyses in adults with T2DM and young adults have shown that late-night eating over 3 days impairs postprandial glucose.[22,42] Our findings suggest that evening meal timing and regularity can significantly influence overnight glycemic variability in individuals with GDM, providing a potential behavioral target to improve glucose stability.

Although prior studies in GDM reported associations between shorter objectively measured sleep duration (5–6 day) and higher veinous fasting glucose levels and post-OGTT glucose,[13,43] we found no association between sleep duration and overnight glucose levels in our study. Participants reported an average of 8 ± 2 h of sleep, consistent with the adult recommendations for optimal health.[44] This suggests that our sample consisted generally of patients with sufficient reported sleep duration, which may partly explain the absence of significant associations. Research suggests that <7 h or > 9 h of sleep is associated with adverse health outcomes, including hyperglycemia and GDM.[45–47] Differences in study design, sleep assessment methods, small sample size, and the short study duration may have limited our ability to detect associations. Moreover, concurrent assessment of sleep and eating patterns may have attenuated sleep effects. Despite this, trends indicated that 5-day averages or variability in sleep duration, nighttime awakenings, and subjective sleep quality could relate with overnight glucose measurements, with combined sleep and eating patterns explaining up to 40% of its variability. Prior research demonstrates that poor sleep quality is associated with higher HbA1c in both pregnant and non-pregnant individuals,[48] and in adults with T1DM, poor sleep quality correlates with greater overnight glycemic variability.[15] However, overall meal timing and regularity had a more pronounced impact on overnight and morning glucose than sleep quality or quantity.

Significant day-to-day variations in overnight and morning glucose measurements were observed across the days of CGM wear, even after excluding day 1. Differences were most pronounced between day 2 (i.e. 32–39 h after insertion) and later days, with mean overnight glucose increasing by up to 0.65 mmol/L and glucose levels upon waking increasing by up to 0.35 mmol/L. This may have clinical significance for GDM management and underscores the importance of sensor calibration using capillary measures. Although the performance of this CGM is generally accurate in pregnant individuals with pre-existing diabetes,[49] uncertainties remain regarding its accuracy and optimal use in individuals with GDM.[9] Our results are consistent with studies outside of pregnancy which have reported reduced sensor accuracy at least during the first day of use.[7] The accumulation of neutrophils and later macrophages at the sensor-tissue interface has been associated with a decrease in sensor accuracy.[50] In addition, pregnancy represents an immunomodulatory state characterized by systematic changes in inflammatory and immune activity, which may promote local inflammation at the sensor insertion site and thereby contribute to lower glucose readings, even at the second day of sensor use.[51]

This study has several strengths. To our knowledge, it is the first to investigate associations between different eating and sleep patterns with overnight and morning blood glucose levels in GDM using CGM under free-living conditions. This study investigates multiple modifiable behaviors affecting glycemic levels and variability, providing a more comprehensive understanding of lifestyle effects on glucose control. Limitations include a small sample size limiting generalizability of between-person findings, though repeated-measures design enhances power for within-person effects. Exploratory stepwise analyses, while useful for hypothesis generation, warrant caution in interpretation due to the risk of overfitting. Future studies should validate findings in larger cohorts using confirmatory approaches (e.g., pre-specified models). We prioritized effect sizes and confidence intervals to facilitate transparent evaluation of clinical relevance. CGM use in a normoglycemic population or in women with GDM may be controversial, as the sensor is validated for diabetes and may limit accuracy for capturing subtle glucose fluctuations within normal ranges.[52,53] Although overnight CGM values have been associated with offspring outcomes,[6] the metrics used to assess glucose control in GDM remain under discussion[54,55] and, while proposed, do not specifically target overnight values. In addition, the short monitoring period, lack of CGM calibration, and the evaluation of an untreated GDM population in a single center may limit generalizability to other clinical settings or to individuals receiving pharmacological treatment. Although snack and dinner carbohydrate content were recorded, the information lacked sufficient detail for most participants and could not be analyzed. Furthermore, the duration of the study was limited and important behavioral and physiological factors, including stress, physical activity, and objective sleep measures were not assessed, potentially limiting our ability to account for these confounding factors, which may have an influence on the observed results. Despite these limitations, our findings highlight the importance of addressing night eating patterns, specifically their timing and regularity, as a potential strategy to improve overnight blood glucose levels in patients with GDM. Future research should incorporate larger and more diverse cohorts, longer and calibrated CGM monitoring, include additional behavioral and physiological factors, use objective assessment of sleep measures, integrate longer study durations, and subsequently interventional designs targeting meal timing and regularity.

Overall, in patients with GDM, overnight and early morning glucose levels are influenced by a complex interplay of medical, dietary, and behavioral factors. Our results demonstrate significant day-to-day variability in CGM and suggest that sensor stabilization may extend beyond the first day of wear during pregnancy. This underscores the need for caution when interpreting single day overnight or early morning glucose values, particularly of the second sensor wear day, when making clinical decisions such as initiating overnight insulin treatment or adjusting lifestyle interventions. To improve sensor accuracy during this period, sensor calibration may improve the accuracy of CGM-derived metrics in patients with GDM.

In clinical practice, our findings underscore the potential value of incorporating meal timing into routine prenatal nutrition counseling for patients with GDM. Current dietary recommendations emphasize on optimizing carbohydrate quality and quantity.[27–29] Adding a temporal component, as also highlighted in a recent review, may offer a

complementary strategy in GDM management.[56] Assessment of meal timing should be included in routine screening, as promoting more consistent day-to-day eating schedules, earlier dinner times, and reducing fixed late-evening snacks could help improve overnight glucose regulation. The interpretation of glucose measurements from a single day should be approached with caution, particularly during the initial days of CGM wear.

Moreover, variability in late-night snack consumption and later dinner timing are associated with adverse overnight glucose levels in patients with GDM. These results underscore the importance of assessing mealtime and regularity in routine clinical care for patients with GDM, as this may help identify individuals at higher risk of suboptimal glycemic control and guide personalized interventions. Based on our findings, patients with GDM may benefit from earlier dinner times and consistent day-to-day eating routines, which may help optimize overnight glycemic control and improve overall metabolic outcomes. Taken together, these findings have direct implications for clinical management of GDM.

CRediT authorship contribution statement

Mariana Treviño Montemayor: Writing – original draft, Investigation, Data curation, Conceptualization. **Alevtina Ackerer:** Writing – review & editing, Data curation. **Alain Lacroix:** Writing – review & editing, Formal analysis. **Tinh-Hai Collet:** Writing – review & editing. **Olivier Le Dizes:** Investigation, Conceptualization. **Dan Yedu Quansah:** Writing – review & editing. **Jardena J. Puder:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

Role of the funding source

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Declaration of competing interest

The authors declare having no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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