Contents available at ScienceDirect

Diabetes Research and Clinical Practice

journal homepage: www.elsevier.com/locate/diabres

International Diabetes Federation

Review

Sleep characteristics in young adults with type 1 diabetes

Stephanie Griggs[*], *Nancy S. Redeker*, *Margaret Grey*

Yale University, School of Nursing, United States

ARTICLE INFO

Article history:
Received 8 November 2018
Received in revised form
18 January 2019
Accepted 13 February 2019
Available online 18 February 2019

Keywords:
Type 1 diabetes
Sleep
Glycemic control
Self-management

ABSTRACT

Only 14% of young adults with Type 1 Diabetes (T1D) achieve targets for glycemic control (HbA1C < 7.0%), with deterioration over time. Complex cognitive processes required to manage glycemia are vulnerable to sleep deficiency. Using Whittemore and Knafl's approach, we conducted an integrative review of research literature on sleep characteristics and glycemia in these young adults. Quality was assessed using the Mixed Methods Appraisal Tool (v. 2011). Multiple databases were searched for articles published in English in peer-reviewed journals from 2003 to 2018, using search terms 'sleep' and 'T1D' with age limiters 18–40. Of 218 studies initially retrieved, 17 original studies met the inclusion criteria. The following themes were identified in young adults with T1D: (1) They had poorer objective and subjective sleep quality, more variability, and impaired awakening response to hypoglycemia compared with controls; (2) They had poorer glycemic control that was associated with shorter sleep duration, poorer sleep quality, and less time in deep sleep; and (3) Hypoglycemia negatively impacted diabetes management, sleep quality, and next day functioning. Sleep deficiency, as indicated by short sleep duration is associated with a range of negative health outcomes for people with T1D; therefore, optimizing sleep should be a priority in practice and research.

Contents

* Corresponding author at: Yale University, School of Nursing, 400 West Campus Drive, Orange, CT, United States.
E-mail addresses: stephanie.griggs@yale.edu, stephaniegriggs83@aol.com (S. Griggs).

https://doi.org/10.1016/j.diabres.2019.02.012
0168-8227/

1. Introduction

Only 14% of young adults age 18–26 years with Type 1 Diabetes (T1D) achieve glycemic control targets (HbA1C < 7.0% or <53 mmol/mol), with deterioration over time from 2010 to 2014 (HbA1C 8.7 vs. 8.3%) based on T1D Exchange Clinic Data [1]. In order to effectively self-manage T1D, individuals must communicate with multiple health professionals [2], check glucose levels multiple times a day and respond to results, prepare optimal foods, and engage in regular physical activity [3]. Self-management is complex [2,4] and requires active problem solving [5], sustained attention [6], planning, coordination, and monitoring of actions (executive function) [7] to optimize glycemic control. These processes are particularly vulnerable to deficiency in sleep duration [8]. Maintaining glycemic control is critical to prevent or delay microvascular and macrovascular complications [9,10].

Problems with sleep duration, quality, and circadian timing are associated with abnormal glucose metabolism [11] and higher obesity and diabetes risk in healthy adults [12]. Improving sleep defiency may also improve glycemic outcomes, but the emphasis in previous studies has been on exploring sleep and glycemia in people with or without type 2 diabetes [13,14]. Thus, the purpose of this review was to integrate the literature on sleep characteristics in young adults with T1D and to identify associations between sleep characteristics and glycemic control.

2. Materials and methods

2.1. Data sources

We systematically searched databases (PubMed, CINAHL, Academic Search Premier, Web of Science) to identify primary research on sleep characteristics in young adults with T1D using search terms: “sleep” and “type 1 diabetes”. We limited our search to studies published in English, in peer-reviewed journals, between the years 2003 to 2018 to capture the timeframe of the Diabetes Control and Complications Trial (DCCT).

2.2. Study selection

We included studies that with young adult participants between the ages of 18–40 years who had T1D and reported sleep characteristics with subjective (e.g., self-report) and/or objective measures (e.g., polysomnography [PSG], or actigraphy). We identified two other systematic reviews on sleep and glycemic control, one on type 2 diabetes [15], and the other on children, adolescents, and adults with T1D [16]. To our knowledge, this is the first review on sleep characteristics and diabetes outcomes in young adults with T1D ages 18–40 years. Articles were screened independently based on the relevance of titles and abstracts by two authors (SG, MG). In addition, four authors from relevant sources were contacted to determine work not captured in the review years that were included. The search yielded 218 references. After removing 33 duplicates, 105 abstracts and 80 full texts were scanned for inclusion (Fig. 1) yielding 17 quantitative studies.

2.3. Data extraction and quality assessment

The first author extracted data from eligible studies and placed them into a standardized extraction template that included purpose, sample, methods, setting, and results. We assessed each study using two criteria of methodological rigor and data relevance on a 2-point scale (high or low) [17]. Quality was assessed using the Mixed Methods Appraisal Tool (v. 2011) based on study type (e.g., randomized controlled

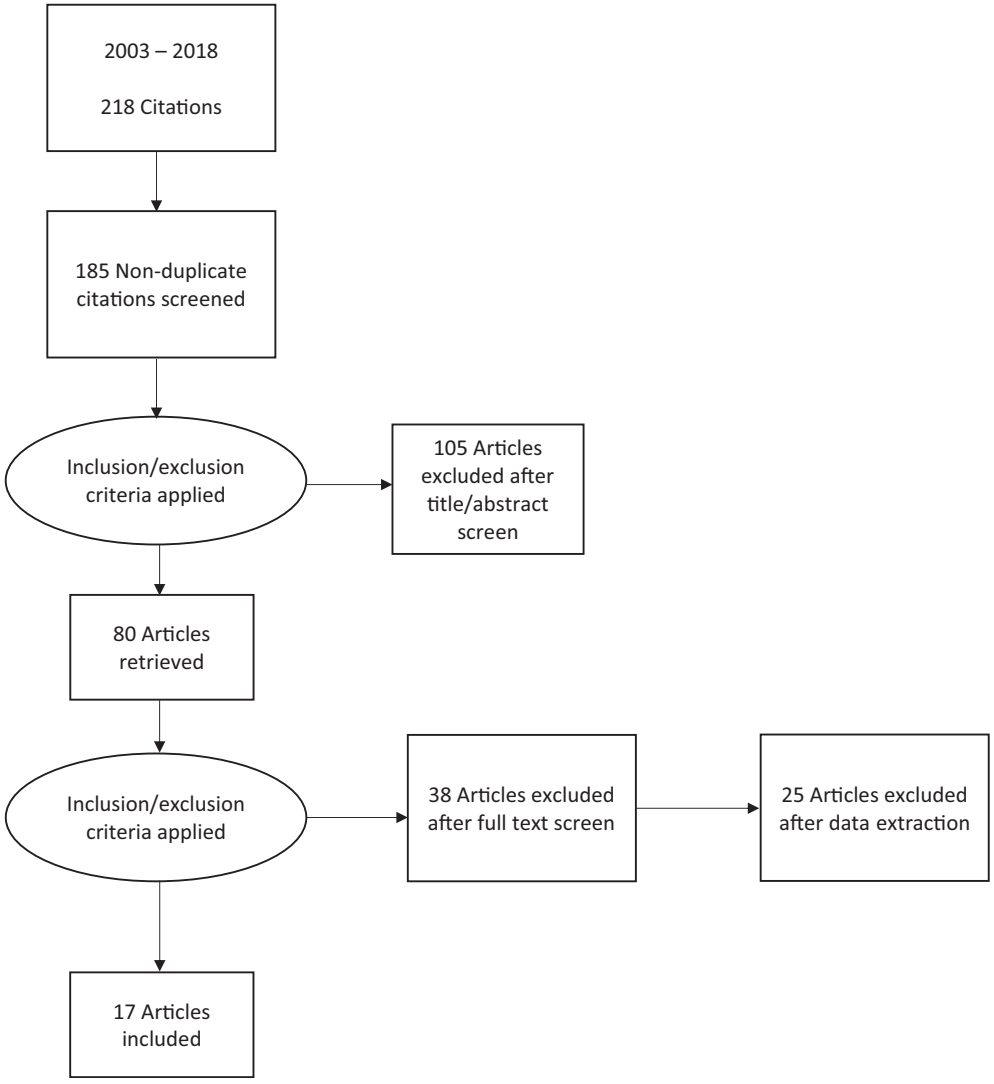

Fig. 1 – Sleep Characteristics in Type 1 Diabetes Search Strategy. Inclusion criteria for search: **(1) primary research; (2) key terms "sleep" and "type 1 diabetes"; (3) published in English from 2003 to 2018.** Inclusion criteria for studies: **(1) young adult participants between the ages of 18–40 years who had T1D; and that (2) reported sleep characteristics with subjective (e.g., self-report) and/or objective measures (e.g., polysomnography [PSG], or actigraphy.**

trials [RCT], non-randomized, or descriptive) [18]. Studies were rated as *high* rigor if two out of four criteria were met (e.g. quality score was $\geq$ 50%). Relevance was coded as high if the study was directly related to question of interest. See Table 1 for study and quality rating.

3. Results

3.1. *Overview of included papers*

The studies included were: ten descriptive (observational cohort studies ranging from seven hours to ten days of sleep assessment and one retrospective cross-sectional survey), three non-randomized, and three randomized clinical trials. In nine studies, sleep characteristics were compared between people with T1D and control participants matched by age, BMI, and/or gender. A total of 529 participants with T1D and 176 control participants were included in this analysis. For participants with T1D vs. controls across the studies, mean age ± SD was 28.5 ± 4.8 vs. 28.2 ± 3.2 and mean BMI ± SD was 24.6 ± 1.3 vs. 23.1 ± 1.4. Mean HbA1C ± SD for participants with T1D was 7.8 ± 0.4% (62 mmol/mol). Study characteristics, sleep measures, and diabetes-related outcomes are shown in Table 1.

3.2. *Sleep measurement*

Both objective (n = 15 studies) and self-report measures (n = 8 studies) of sleep characteristics were used. Sleep duration, sleep efficiency, and variability of sleep duration, as well as specific sleep disorders were the most commonly reported sleep characteristics. PSG is a multi-parametric test used in the study of sleep [19] that distinguishes sleep stages (rapid eye movement [REM], nonrapid eye movement [NREM]) using electro-encephalography (EEG), electro-oculography (EOG), and electro myelography (EMG) [19], and cardiac and

Table 1 – Characteristics of the studies and their sleep variables included in the analysis.

Study	Setting	T1D participants				Control participants			Study design	Sleep measurement	Sleep characteristics and outcome variables	Quality Rating
		N	Age (y) ± SD	BMI (kg/m^2)	HbA1c (%)	N	Age (y) ± SD	BMI (kg/m^2)				
Studies comparing sleep in type 1 diabetes vs. control participants												
Adler et al. [23]	Israel	64	21.96 ± 3.21	N/A	7.46	64	25.20 ± 3.74	N/A	Descriptive, cross sectional, matched control (age)	Self-report: PSQI, ESS	Duration, quality + depression, and glycemic control	Rigor: high Relevance: high
Banarer and Cryer [24]	Washington, United States	8	27.0 ± 7.4	26.4	8.3	8	27.4 ± 7.1	26.0	Non-randomized	Objective: PSG	Sleep stages, SE + plasma c-peptide, induced hypoglycemia	Rigor: low Relevance: high
Barone et al. [22]	Brazil	18	26.3 ± 5.1	23.0	7.8	9	28.8	22.0	Descriptive, observational over 10 days, matched controls (age and BMI)	Objective: PSG actigraphy × 10 days Self-report: ESS, sleep diary	TST, quality + glycemic control	Rigor: high Relevance: high
Janovsky et al. [27]	Brazil	20	27.0 ± 8.2	22.1	7.5	22	23.2 ± 3.9	21.8	Descriptive, observational overnight	Objective: PSG, electrocardiogram, electroencephalogram Self-report: ESS	TST, SE, microarousals, REM, NREM stages 1–4, sleep apnea + oximetry	Rigor: high Relevance: high
Jauch-Chara, et al. [39]	Germany	14	31.3 ± 2.6	24.4	7.7	14	28.4 ± 1.5	23.0	Descriptive, observational 2 nights (adaptation + observation)	Objective: PSG	TST, Circulating glucose, insulin, glucagon concentrations	Rigor: high Relevance: high
Jauch-Chara et al. [21]	Germany	14	31.3 ± 2.6	24.2	7.7	14	28.9 ± 1.5	23.1	Non-randomized	Objective: PSG Subjective checklist (EWL)	TST, WASO, REM, NREM stages, plasma glucose, serum insulin, GH, epinephrine, ACTH, cortisol	Rigor: high Relevance: high
Jauch-Chara et al. [38]	Germany	16	31.3 ± 2.6	24.4	7.7	16	28.4 ± 1.5	23.0	Non-randomized	Objective: PSG	Sleep stages + hypoglycemia, declarative memory	Rigor: low Relevance: high
Perfect et al. [29]	US	7	34.99 ± [a,b]	[a]	8.79[b]	13	34.99 ± [a,b]	[a]	Descriptive, feasibility study over 1 week	Objective: actigraphy Self-report: PSQI	TST, SOL, SE, WASO, quality + salivary cortisol, positive and negative affect, coping	Rigor: high Relevance: high
Schultes et al. [38]	Germany	16	31.3 ± 2.6	24.4	7.7	16	28.4 ± 1.5	23.0	RCT	Objective: PSG	TST, SOL, slow wave sleep time + induced hypoglycemia and euglycemia	Rigor: high Relevance: high
Studies exploring sleep characteristics and diabetes related outcomes												
Borel et al. [32]	France	79	40[c]	23.3	7.9	–	–	–	Descriptive, observational over 3 days	Objective: Actigraphy Self-report: PSQI, BQ	Duration (short < 6.5 h vs. normal > 6.5 h), latency, efficiency, fragmentation + restless legs, diabetes-related QOL, microalbuminuria	Rigor: high Relevance: high
Farabi et al. [26]	US	24	23.8 ± 3.9	26.0	7.8	–	–	–	Descriptive, observational over 7 h	Objective: PSG	TST, sleep apnea, NREM, REM + glycemic control, IL-6, TNF-α	Rigor: high Relevance: high
Farabi et al. [20]	US	27	23.8 ± 4.1	26.0	7.9	–	–	–	Descriptive, observational overnight	Objective: PSG and actigraphy	TST, SOL, SE, WASO, Awakenings	Rigor: high Relevance: high
Farabi et al. [20]	US	23	24 ± 4.0	25.9	7.6	–	–	–	Descriptive, observational overnight	Objective: PSG & actigraphy	TST, REM and NREM, SE, SOL, arousals, awakenings, WASO + glycemic control	Rigor: high Relevance: high
Farabi et al. [26]	US	27	23.8 ± 4.1	26.0	7.9	–	–	–	Descriptive, observational over 60 h	Objective: PSG & actigraphy	TST, REM and NREM, SE, SOL, arousals, awakenings, WASO + glycemic control	Rigor: high Relevance: high
Matejko et al. [40]	Poland	148	26.3 ± 9.0	23.3	7.2	–	–	–	Descriptive, retrospective, cross sectional survey	Self-report: sleep duration	Duration and glycemic control	Rigor: low Relevance: high
Experimental studies												
Inkster et al. [33]	Scotland	14	27.5 ± [a]	25.9	8.0	–	–	–	RCT	Objective: text messaging	Sleep deprivation + glycemia	Rigor: low Relevance: high
Reddy et al. [31]	US	10	33 ± 6	24.4	7.4	–	–	–	RCT (pilot) 3 week crossover	Objective: actigraphy Self-report: PSQI, ESS, BQ	TST, sleepiness, apnea, quality, SOL + exercise, glycemia	Rigor: high Relevance: high

Key Terms: ACTH: Adrenocorticotropic Hormone, BQ: Berlin Questionnaire, 10-item risk factors for obstructive sleep apnea, CGM Continuous Glucose Monitor, ESS: Epworth Sleepiness Scale, 8-item, EWL: Standardized Adjective Checklist, GH: Growth Hormone, HbA1C: Hemoglobin A1C, NREM: Non-rapid Eye Movement Sleep, PSQI: Pittsburg Sleep Quality Index, 19-item, PSG: Polysomnography, REM: Rapid Eye Movement Sleep, SE: Sleep Efficiency, TNF-α: Tumor Necrosis Factor Alpha, TST: Total Sleep Time, WASO: Wake After Sleep Onset.

[a] Data not available.

[b] Only total sample characteristics (age, BMI, A1C) provided (N = 2108; type 1 and type 2).

[c] Median age provided.

respiratory data depending on the purpose of the study. Wrist actigraphy estimates sleep quality and quantity in the natural environment from motor activity as a surrogate for wakefulness [20]. Based on a validation study of wrist actigraphy in 27 young adults with T1D, mean differences between the actigraphy and PSG were not significant ($p > 0.65$) for all sleep parameters except sleep onset latency ($p = 0.04$); therefore, the low threshold setting was recommended to estimate sleep parameters most accurately [20].

3.3. Sleep characteristics

3.3.1. Sleep in people with T1D and controls

In nine studies, sleep characteristics of people with T1D and matched controls without diabetes were compared. People with T1D spent less time in slow wave sleep [21], had more pronounced sleep extension on the weekends [22], and reported poorer quality [23] and less restorative sleep [21]. There were no differences in subjectively reported or objectively recorded sleep duration, objective sleep efficiency [22,24], or prevalence of self-reported hypersomnolence [23], between young adults with T1D and matched controls [22,23].

3.3.2. Sleep duration

The National Sleep Foundation (NSF) recommends that young adults obtain 7–9 h of sleep per night (420–540 min) [25]. Total sleep time (TST) was obtained through PSG (10 studies), actigraphy (7 studies), and/or self-report (6 studies). The range of TST was 372.8 min (6.2 h) [26] to 430 min (7.2 h) [22]. In the majority of studies, those with T1D slept < 400 min (6.6 h). Young adults with T1D had comparable subjective [22,23] and objective sleep duration [22] with matched controls. In Barone et al.'s [22] study, TST measured with PSG in people with T1D vs. matched controls was 431 ± 54 (7.2 h ± 0.9 h) vs. 456 ± 43 (7.6 ± 0.7 h) minutes respectively ($p > 0.05$).

3.3.3. Sleep architecture

In the10 studies that included PSG, stage REM and sleep stages (N1, N2, N3) were reported in three [21,26,27]. In young adults with T1D, stage N1 ranged from 6.4% [26] to 14.2% [21], stage N2 ranged from 51.1% [26] to 55.6% [21], stage N3 ranged from 14.7% [21] to 22.6% [27], and REM ranged from 13.9% [21] to 21.4% [26]. Compared with controls, adults with T1D had a higher proportion of stage N2 and a lower proportion of stage N3 under euglycemic conditions [21]. In contrast, nocturnal hypoglycemia was associated with a higher proportion of stage N3 sleep [21]. For example, during hypoglycemic conditions, 14 participants with T1D spent more time in stage N3 compared to controls ($p = 0.02$) [21]. Therefore, it is important to consider glycemia, particularly hypoglycemia, as a confounder when assessing sleep architecture in this population.

3.3.4. Objective sleep quality and sleep efficiency

Overall sleep quality includes duration (desirable 7–9 h), efficiency (desirable ≥ 85%), sleep fragmentation (desirable ≤ 25), (measured with PSG or actigraphy) and appropriate sleep staging (REM ≤ 41%, N1 ≤ 5%, N2 ≤ 20%, N3 > 5%) as measured with PSG [28]. Sleep efficiency was reported in six studies [20,24,26,27,29,30]. Five studies had PSG and actigraphy and one had actigraphy only [31]) and sleep efficiency ranged from 77 ± 18% [24] to 88.4 ± 5.5% in participants with T1D [27]. Differences in sleep staging were not observed in a descriptive study of 18 young adults with T1D and 9 controls (control vs. T1DM - % of REM sleep: 21.5% ± 5.3% vs. 19.9% ± 7.7%, $p = 0.62$; % stage N3, 21.7% ± 8.4% vs. 20.6% ± 8.3%: $p = 0.77$) [22]. Under experimental hypoglycemic conditions (<45 mg/dL), sleep efficiency measured by PSG was poorer in participants without diabetes ($n = 8$, mean age 27.4 ± 7.1 years) compared to those with T1D ($n = 8$ mean age 27 ± 7.4 years) (sleep efficiency = 26 ± 8 vs. 77 ± 18%, $p = 0.01$ respectively) [24].

3.3.5. Self-reported sleep quality

People with T1D often reported poor subjective sleep quality (global PSQI score ≥ 5) [29]. PSQI-measured global sleep quality scores were reported in four studies [23,29,31,32] and ranged from 3.2 [23] to 9.2 [29] and were negative correlated with age ($r = -0.266$, $p = 0.035$) and diabetes duration ($r = -0.281$, $p = 0.026$) [23].

3.3.6. Sleep variability

Varying day-to-day schedules or weekday-to-weekend differences in sleep duration may reflect alternating between sleep deprivation and compensation and shifts in circadian timing. Young adults with T1D may experience more sleep variability in duration than those without T1D. In an observational study, 18 young adults with T1D (mean age 26.3 ± 5.1 years) had a more prononouced sleep extension on weekends compared to 9 control individuals (2 h 01 min 33 s ± 1 h 07 min 19 s vs. 57 min 17 s ± 36 min 24 s respectively; $p = 0.03$) [22]. Sleep variability may be an important consideration for young adults with T1D; however, the work in this population is limited.

3.4. Sleep disorders

Researchers evaluated obstructive sleep apnea (OSA) [20,27] and self-reported OSA risk [32,33]. OSA in adults is characterized by repetitive cessation of breathing episodes (apnea) or partial airway obstruction [34]. OSA was measured with PSG and/or oximetry and was defined as an apnea/hypopnea index ≥ 5 events/hour or repetitive pathologic oximetry [35]. Severity of OSA was associated with older age [32], longer duration of diabetes [32], retinopathy [32], hypertension [32], and cardiovascular autonomic neuropathy [27,36].

Prevalence of OSA in young adults with T1D was 23%-67% [27]. Among young adults with T1D ($n = 20$) and controls without diabetes ($n = 22$), individuals with cardiovascular autonomic neuropathy (CAN) had a higher prevalence of OSA compared to the other groups (67% CAN+; 23% CAN−; 4.5% controls: CAN+ vs. Control; $p = 0.006$ and CAN+ vs. CAN-; $p = 0.02$) [27]. The CAN- group had higher sleep efficiency compared to the CAN+ group [27].

3.5. Sleep and glycemia

3.5.1. Hypoglycemia

Hypoglycemic events (fasting blood sugar < 70 mg/dL) [37] were associated with reduced actual awakenings [24,38], reduced REM, or light sleep [21], impaired declarative memory

[33,39], poorer general alertness and motor speed [33], EEG changes [26], and previous exercise among young adults with T1D [31]. Hypoglycemic events were more prolonged in people with T1D who exhibited blood pressure dipping compared to blood pressure non-dipping [37].

People with T1D may experience nocturnal hypoglycemia following daytime aerobic exercise [31]. As demonstrated in a 3-week crossover trial, nocturnal hypoglycemia occurred more on nights following aerobic and resistance exercise [31]. In two studies, young adult participants with T1D were found to have an impaired awakening response to lowered plasma glucose [24,38]. In a RCT, plasmaepinephrine ($p < 0.001$), norepinephrine ($p < 0.084$), and pancreatic polypeptide ($p < 0.003$) responses to hypoglycemia were reduced during sleep in subjects with T1D (final awake versus asleep values were 240 ± 86 and 85 ± 47, 205 ± 24 and 148 ± 17, and 197 ± 45 and 118 ± 31 pg/ml, respectively) [24].

Hypoglycemia affects cognitive function (memory, general alertness, and motor speed), however, sleep deprivation does not seem to worsen the effect in this population. For example, in a randomized pilot intervention study of induced sleep deprivation and hypoglycemia (compared to normal sleep time) in 14 young adults (mean age 27.5 years), although hypoglycemia produced a significant decrease in cognitive function (digit symbol substitution scores and choice reaction times), coexisting sleep deprivation did not have an additive effect [33]. However, once normoglycemia was restored, sleep deprivation was associated with persistence of hypoglycemic symptoms ($\beta = 0.87$, $p < 0.001$) on subsequent days and more prolonged cognitive dysfunction during the recovery period ($\beta = 0.34$, $p < 0.001$) after one night of total sleep deprivation [33].

3.5.2. *Hyperglycemia*

Hyperglycemia (fasting blood sugar > 150 mg/dL) [37] and higher average daily glucose values were associated with increased sleep onset latency and a higher awakenings index, but hyperglycemia and sleep duration were not related [22]. Osmotic diuresis associated with hyperglycemia (polyuria) may disrupt sleep due to increased nocturia. There has been little research that has investigated the direct effect of hyperglycemia on sleep characteristics.

3.5.3. *Glycemic control*

Glycemic control was positively associated with sleep quality measured with PSG ($r = 0.65$, $p = 0.01$) [22], while poorer glycemic control was associated with shorter sleep duration [32,40] and OSA [27]. Higher glucose levels were correlated with longer sleep onset latency, more awakenings, and poorer sleep quality [22]. Glycemic variability (SD) was positively correlated with sleep onset latency ($r = 0.65$, $p = 0.003$); HbA1C was positively correlated with the full awakening index and the arousal index ($r = 0.65$, $p = 0.008$; and $r = 0.57$, $p = 0.03$, respectively); and mean glucose values were negatively correlated with sleep quality in individuals with normal glucose levels (mean < 154 mg/dL) in 18 young adults with T1D [22].

Short TST is negatively associated with glycemic control and a nocturnal blood pressure non-dipping pattern in young adults with T1D. Young adults with T1D who slept ≤ 6.5 h had poorer HbA1C levels than those who slept > 6.5 h ($p < 0.01$) [32,40]. Young adults with T1D who slept ≤ 6.5 h ($n = 21$) had higher HbA1C than those who slept > 6.5 h ($n = 58$) (HbA1C 8.5 vs. 7.7%, $p = 0.01$) and sleep duration was the only sleep variable associated with HbA1C ($R^2 = 10\%$) (not diabetes duration, diabetes quality of life, or daily activity) [32]. In another study of 148 young adults, shorter TST was associated with poorer glycemic control (($\beta = 0.51$, $p = 0.01$) [40]. In contrast, results of another study ($n = 18$ young adults with T1D and $n = 9$ controls) suggested that the correlation between TST and glycemic control was not significant [22].

4. Discussion

We found that poor sleep quality, sleep deficiency, and higher variability in sleep duration were common in young adults with T1D; however, TST was not significantly different compared to age, gender, and BMI matched controls. Young adults with T1D had poorer sleep quality (e.g., lower sleep efficiency, less time in N3 sleep), more variability, less restorative sleep, and an impaired awakening response to hypoglycemia compared with matched controls. Failure to awaken from sleep increases the risk for those with T1D to suffer prolonged and potentially fatal hypoglycemia [41]. It is likely that when T1D is coupled with a sleep disorder, cardiovascular risk is increased [27]. Insomnia has previously been associated with metabolic dysregulation [42,43] and was not addressed in the studies in this review. Also, there has been limited research to determine if the prevalence of sleep disorders is higher in young adults with T1D, but CAN may play an essential role in the physiopathology of OSA based on one study [27].

Self-managing T1D requires sustained attention [6], and executive function [7] to optimize glycemic control. With these processes being vulnerable to sleep deficiency [8], improving sleep duration (7–9 h) may in turn result in improved glycemic control. Only preliminary work has been done to extend sleep in young adults with T1D ($N = 8$) [44]. Perfect and colleagues designed an intervention to extend sleep by 1 h in adolescents ($N = 111$) which led to a preliminary 7.4% improvement in mean glucose levels measured from CGM [45,46]; however, the applicability of this intervention in young adults needs to be further evaluated.

Young adults are transitioning to independence and may be living on their own, with a roommate, with a significant other, and/or starting a family. There is an identified need for interventions involving parental assessment of sleep in younger populations (e.g., children and adolescents) with T1D [47–51]. To our knowledge there are no intervention studies in which reduction of fear of nocturnal hypoglycemia for those living with or directly involved in a young adult's T1D management is targeted. Practitioners working with young adults with T1D need to manage expectations and fears associated with nocturnal hypoglycemia as these issues may contribute negatively to sleep quality and shorter sleep duration.

Technologies such as continuous glucose monitors and insulin pumps that can sense and stop insulin infusions when blood glucose is low have the potential to reduce the fear of and actual hypoglycemia. In some studies closed-loop systems combining computer-based algorithms for insulin therapy are beginning to demonstrate reductions in sleep

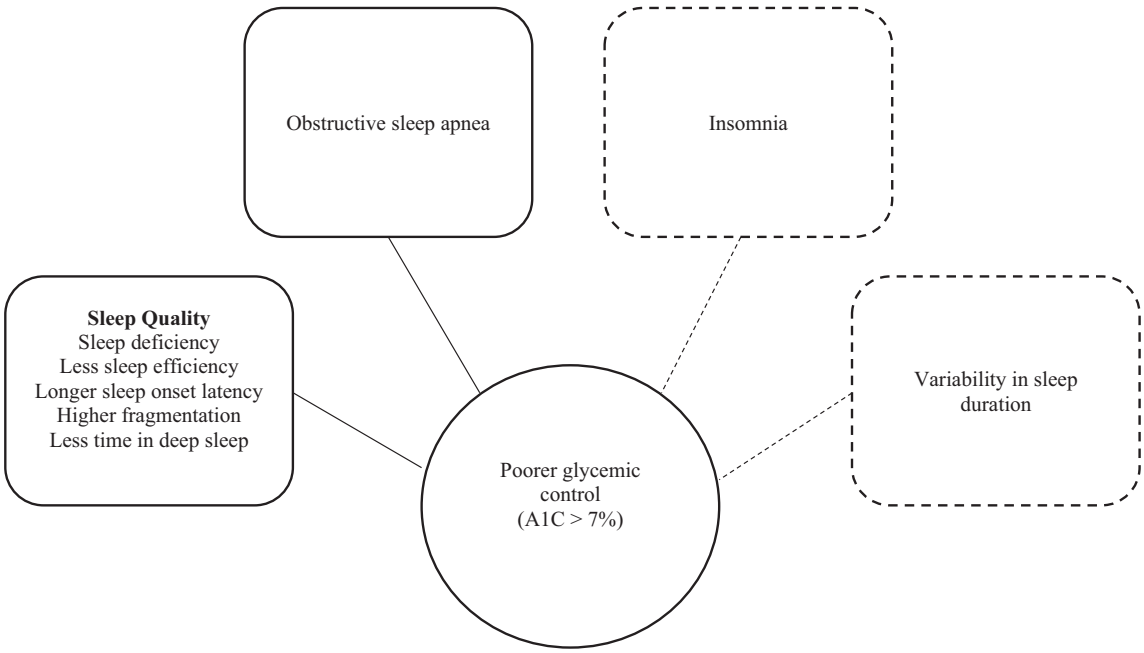

Fig. 2 – Proposed Model of the Associations between Sleep Characteristics and Glycemic Control in T1D. Note: Solid line indicates known sleep factors associated with poorer glycemic control in young adults. Dotted line indicates a known sleep factor associated with poorer glycemic control in other ages. Key for defining variables: **Sleep deficiency (≤6.5 h), less sleep efficiency (<85%), Longer sleep onset latency (>30 mins, Higher fragmentation (>25), Less time in deep sleep (<5%).**

disturbances for caregivers and adolescents with T1D [48,52]; however in one study of 16 adults (mean age 42.1 years) and 12 adolescents (mean age 15.2 years), no differences were noted in self-reported sleep quality for those with T1D using a closed-loop system or insulin pump [53]. Further, only <7% of young adults use a CGM [54], a finding that warrants the need for a better understanding in this age group about the barriers and facilitators of the use of such diabetes technology. While it is likely that time is required to acclimate to new T1D management systems, these devices have great potential to improve sleep duration for young adults who use these devices.

The trials we reviewed were focused on shortening sleep or inducing hypoglycemia and the effect on glycemic control. Results may be confounded due to the use of different instruments to measure sleep, underlying sleep disorders, over-reliance on self-report, and inconsistency in defining sleep characteristics. Although PSG is the gold standard for objective measurement of sleep architecture and quality, it can be burdensome and may not capture normal sleep, as a laboratory is not the natural sleeping environment. There is agreement between PSG and actigraphy in TST, sleep efficiency, wake after sleep onset, and number of awakenings with PSG on the low setting [20], so actigraphy appears to be a reliable alternative for objectively measuring sleep in young adults with T1D in the natural environment. Nonetheless, sleep onset latency should be interpreted with caution due to poor agreement between PSG and actigraphy for this variable [20].

Different approaches were used to measure glucose (CGM vs. HbA1C) to determine glycemic control. In the future, researchers should consider the concurrent examination of both glucose variability and HbA1C based on ADA (2018) recommendations. Other potential confounding factors related to sleep characteristics in young adults with T1D are the duration of diabetes, age, race, and varying contextual factors at the time of each study. For example, it may be that there is lower impairment of sleep with longer experience of diabetes self-management based on the negative association of age and self-reported sleep quality [23]. Some of the authors focused on causative factors on sleep variables while others examined the impact of sleep on select outcomes (primarily glycemic control).

While TST was not shorter in people with T1D compared to controls, it was still less than 6.6 h on average. Other sleep characteristics, such as sleep quality were poorer in young adults with T1D compared to matched controls. Sleep variability may be an important consideration for glycemic control in this population, but this was reported in only one study of young adults with T1D and associations with glycemic control were not explored. Researchers found higher glycemic values and insulin resistance following interventions that shortened sleep. Thus, optimizing sleep duration and quality should be considered as an approach to improve glucoregulation and self-management in young adults with T1D. In Fig. 2, we propose relationships among sleep characteristics and glycemic control. These relationships posited in Fig. 2 should be addressed in context of the limitations of the studies. The studies may not have been powered to detect significance (risk of Type II error), or these contradicting findings could be due to variability in measures of sleep quality or other underlying mechanisms not accounted for in the design. Glycemic control is likely influenced by sleep deficiency over time, however, causal inference remains unclear.

More high-quality studies of sleep with larger samples conducted over time are needed to provide a more precise conceptualization of sleep characteristics in T1D and their relationship with glycemic control. Researchers should consider how diabetes technology, social relationships, and biology may impact the pathways in the proposed model.

4.1. *Limitations*

A strength of this review is its specific focus on sleep characteristics in young adults with T1D who are at high risk based on their relatively poor rates of glycemic control (14%) [1]. We included multiple designs to capture the work in this targeted area. This review does have limitations. This review was not inclusive of gray literature such as unpublished dissertations or studies published in languages other than English. Gray literature may have expanded or clarified the relationship between sleep characteristics and glycemia in young adults with T1D. Also, years were limited to 2003–2018; therefore periodic updates will be important mainly to capture the advances in sleep and glucose measurement. It was difficult to determine differences in sleep stage percentages for young adults with T1D to ascertain if there were differences from same age peers without T1D due to the manipulation of glycemia in several studies. Thus, we included differences noted in two studies reporting the association under euglycemic conditions [21,39], and another study about nocturnal hypoglycemia and the association with stage N3 sleep under naturalistic conditions [22]. More work is needed to elucidate the associations among sleep stages and glycemia under euglycemic or naturalistic conditions to improve our understanding of differences in sleep stages for young adults with T1D compared with same age peers without T1D.

5. Conclusions

The relationships among sleep quality, sleep duration, sleep variability, and self-management in persons with type 1 diabetes are complex and likely bidirectional. Poorer sleep quality, including short sleep duration, poorer sleep efficiency, longer sleep onset latency, higher fragmentation, higher awakening and arousal, and or less time in deep sleep (stage N3) are associated with suboptimal glycemic control, as well as impaired next day functioning and self-management. These conditions are associated with an increased risk of developing microvascular and macrovascular complications [32,37]. Although young adulthood may be characterized as having a lower disease burden, a greater emphasis in research and practice should be placed on these individuals with T1D who have poorer glycemic control.

Sleep is a modifiable risk factor that should be considered in improving self-management and glycemic control in this population in addition to increasing physical activity and maintaining a healthy BMI. Optimizing sleep duration and quality in young adults may in turn improve glycemic control and clinical outcomes; however, further work is needed to confirm these relationships. There have been limited studies aimed at optimizing sleep among young adults, therefore more work is needed to investigate the mechanistic pathways in sleep among young adults with T1D and to develop effective interventions to move the science forward.

Funding

National Institute for Nursing Research (NINR), T32 NR0008346.

Declarations of interest

None.

Acknowledgement and declaration of author contributions

The first author SG drafted and edited the manuscript and conducted the search. The senior author MG verified the search and inclusion criteria, reviewed the content, and edited the manuscript. The second author NSR reviewed the content and edited the manuscript.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.diabres.2019.02.012.

REFERENCES

[1] Miller KM, Foster NC, Beck RW, et al. Current state of type 1 diabetes treatment in the U.S.: Updated data from the T1D exchange clinic registry. Diabetes Care 2015;38(6):971–8.
[2] Grey M, Schulman-Green D, Knafl K, Reynolds NR. A revised self-and family management framework. Nurs Outlook 2015;63(2):162–70.
[3] Karter AJ, Ackerson LM, Darbinian JA, et al. Self-monitoring of blood glucose levels and glycemic control: The northern california kaiser permanente diabetes registry*. Am J Med 2001;111(1):1–9.
[4] Adams KM, Corrigan J, Greiner A. Report of a summit: 1st annual crossing the quality chasm summit: A focus on communities. National Academies Press; 2004.
[5] McNally K, Rohan J, Pendley JS, Delamater A, Drotar D. Executive functioning, treatment adherence, and glycemic control in children with type 1 diabetes. Diabetes Care 2010;33(6):1159–62.
[6] Thomas M, Sing H, Belenky G, et al. Neural basis of alertness and cognitive performance impairments during sleepiness. I. effects of 24 h of sleep deprivation on waking human regional brain activity. J Sleep Res 2000;9(4):335–52.
[7] Jones K, Harrison Y. Frontal lobe function, sleep loss and fragmented sleep. Sleep Med Rev 2001;5(6):463–75.
[8] Durmer JS, Dinges DF. Neurocognitive consequences of sleep deprivation. 2005;25(01):117–129.
[9] Nathan DM. DCCT/EDIC Research Group The diabetes control and complications trial/epidemiology of diabetes interventions and complications study at 30 years: Overview. Diabetes Care 2014;37(1):9–16.
[10] American Diabetes Association. Standards of medical care in diabetes—2017 abridged for primary care providers. Clin Diabetes. 2017;35(1):5–26.

[11] Spiegel K, Leproult R, Van Cauter E. Impact of sleep debt on metabolic and endocrine function. The Lancet 1999;354 (9188):1435–9.
[12] Knutson KL, Van Cauter E. Associations between sleep loss and increased risk of obesity and diabetes. Ann N Y Acad Sci 2008;1129(1):287–304.
[13] Reutrakul S, Van Cauter E. Interactions between sleep, circadian function, and glucose metabolism: Implications for risk and severity of diabetes. Ann N Y Acad Sci 2014;1311 (1):151–73.
[14] El-Aghoury AA, Elsherbiny TM, Lewis N, Salem TM, Osman N. Characterization of abnormal sleep patterns in patients with obesity, type 2 diabetes, or combined. Alexandria J Med 2017;54:455–62. https://doi.org/10.1016/j.ajme.2017.10.004.
[15] Lee SWH, Ng KY, Chin WK. The impact of sleep amount and sleep quality on glycemic control in type 2 diabetes: A systematic review and meta-analysis. Sleep Med Rev 2017;31:91–101.
[16] Reutrakul S, Thakkinstian A, Anothaisintawee T, et al. Sleep characteristics in type 1 diabetes and associations with glycemic control: Systematic review and meta-analysis. Sleep Med. 2016;23:26–45.
[17] Whittemore R, Knafl K. The integrative review: Updated methodology. J Adv Nurs 2005;52(5):546–53.
[18] Pluye P, Gagnon M, Griffiths F, Johnson-Lafleur J. A scoring system for appraising mixed methods research, and concomitantly appraising qualitative, quantitative and mixed methods primary studies in mixed studies reviews. Int J Nurs Stud 2009;46(4):529–46.
[19] Pandi-Perumal S, Spence DW, BaHammam AS. Polysomnography: An overview. In: Primary care sleep medicine. Springer; 2014. p. 29–42.
[20] Farabi SS, Quinn L, Carley DW. Validity of actigraphy in measurement of sleep in young adults with type 1 diabetes. J Clin Sleep Med 2017;13(5):669–74.
[21] Jauch-Chara K, Schmid SM, Hallschmid M, Born J, Schultes B. Altered neuroendocrine sleep architecture in patients with type 1 diabetes. Diabetes Care 2008;31(6):1183–8.
[22] Barone MTU, Wey D, Schorr F, et al. Sleep and glycemic control in type 1 diabetes. Arch Endocrinol Metabol 2015;59 (1):71–8.
[23] Adler A, Gavan M, Tauman R, Phillip M, Shalitin S. Do children, adolescents, and young adults with type 1 diabetes have increased prevalence of sleep disorders? Pediat Diabetes 2017;18(6):450–8.
[24] Banarer S, Cryer PE. Sleep-related hypoglycemia-associated autonomic failure in type 1 diabetes: Reduced awakening from sleep during hypoglycemia. Diabetes 2003;52 (5):1195–203.
[25] Hirshkowitz M, Whiton K, Albert SM, et al. National sleep foundation's sleep time duration recommendations: Methodology and results summary. Sleep Health 2015;1 (1):40–3.
[26] Farabi SS, Carley DW, Quinn L. EEG power and glucose fluctuations are coupled during sleep in young adults with type 1 diabetes. Clin Neurophysiol 2016;127(8):2739–46. https://doi.org/10.1016/j.clinph.2016.05.357.
[27] Janovsky, Silva Carolina Castro Porto, Rolim, de Souza Pereira Luiz Clemente, Sá JRd, et al. Cardiovascular autonomic neuropathy contributes to sleep apnea in young and lean type 1 diabetes mellitus patients. Front Endocrinol 2014;5:119.
[28] Ohayon M, Wickwire EM, Hirshkowitz M, et al. National sleep foundation's sleep quality recommendations: First report. Sleep Health 2017;3(1):6–19.
[29] Perfect MM, Elkins GR, Lyle-Lahroud T, Posey JR. Stress and quality of sleep among individuals diagnosed with diabetes. Stress Health 2010;26(1):61–74.
[30] Farabi SS, Carley DW, Quinn L. Glucose variations and activity are strongly coupled in sleep and wake in young adults with type 1 diabetes. Biol Res Nurs 2017;19(3):249–57.
[31] Reddy R, El Youssef J, Winters-Stone K, et al. The effect of exercise on sleep in adults with type 1 diabetes. Diabetes Obes Metab 2018;20(2):443–7.
[32] Borel AL, Pepin JL, Nasse L, Baguet JP, Netter S, Benhamou PY. Short sleep duration measured by wrist actimetry is associated with deteriorated glycemic control in type 1 diabetes. Diabetes Care 2013;36(10):2902–8.
[33] Inkster BE, Zammitt NN, Ritchie SJ, Deary IJ, Morrison I, Frier BM. Effects of sleep deprivation on hypoglycemia-induced cognitive impairment and recovery in adults with type 1 diabetes. Diabetes Care 2016;39(5):750–6.
[34] Flemons WW, Buysse D, Redline S, et al. Sleep-related breathing disorders in adults: Recommendations for syndrome definition and measurement techniques in clinical research. the report of an american academy of sleep medicine task force. Sleep 1999;22(5):667–89.
[35] Farabi SS, Carley DW, Akasheh RT, Quinn L. Tumor necrosis factor alpha increases following sleep in young adults with type 1 diabetes. Acta Diabetol 2016;53(6):1049–51.
[36] Schober A, Neurath MF, Harsch IA. Prevalence of sleep apnoea in diabetic patients. Clin Respiratory J 2011;5 (3):165–72.
[37] Borel AL, Benhamou PY, Baguet JP, et al. Short sleep duration is associated with a blood pressure nondipping pattern in type 1 diabetes: The DIAPASOM study. Diabetes Care 2009;32 (9):1713–5.
[38] Schultes B, Jauch-Chara K, Gais S, et al. Defective awakening response to nocturnal hypoglycemia in patients with type 1 diabetes mellitus. PLoS Med 2007;4(2):e69.
[39] Jauch-Chara K, Hallschmid M, Gais S, et al. Hypoglycemia during sleep impairs consolidation of declarative memory in type 1 diabetic and healthy humans. Diabetes Care 2007;30 (8):2040–5.
[40] Matejko B, Kiec-Wilk B, Szopa M, Trznadel Morawska I, Malecki MT, Klupa T. Are late-night eating habits and sleep duration associated with glycemic control in adult type 1 diabetes patients treated with insulin pumps? J Diabetes Invest 2015;6(4):460–4.
[41] Weston P, Gill G. Is undetected autonomic dysfunction responsible for sudden death in type 1 diabetes mellitus? the 'dead in bed'syndrome revisited. Diabetic Med 1999;16 (8):626–31.
[42] Depner CM, Stothard ER, Wright KP. Metabolic consequences of sleep and circadian disorders. Curr DiabRep 2014;14(7):507.
[43] Spielman AJ, Caruso LS, Glovinsky PB. A behavioral perspective on insomnia treatment. Psychiatr Clin North Am 1987.
[44] Farabi SS, Broussard JL, Sippl R, et al. Sleep extension and continuous glucose monitoring in adults with type 1 diabetes. 2018;41:A330–A330.
[45] Perfect MM, Beebe DW, Levine-Donnerstein D, Frye SS, Bluez GP, Quan SF. The development of a clinically relevant sleep modification protocol for youth with type 1 diabetes. Clin Pract Pediat Psychol 2016;4(2):227.
[46] Perfect MM, Frye S, Bluez GP. The effects of a sleep extension intervention on glucose control in youth with type 1 diabetes. Diabetes 2018;67(Suppl 1).
[47] Monzon A, McDonough R, Meltzer LJ, Patton SR. Sleep and type 1 diabetes in children and adolescents: Proposed theoretical model and clinical implications. Pediat Diabetes 2018:1–8.
[48] Jaser SS, Foster NC, Nelson BA, et al. Sleep in children with type 1 diabetes and their parents in the T1D exchange. Sleep Med 2017;39:108–15.

[49] Patel NJ, Savin KL, Kahanda SN, et al. Sleep habits in adolescents with type 1 diabetes: Variability in sleep duration linked with glycemic control. Pediat Diabetes 2018;19 (6):1100–6.
[50] Landau Z, Rachmiel M, Pinhas-Hamiel O, et al. Parental sleep quality and continuous glucose monitoring system use in children with type 1 diabetes. Acta Diabetol 2014;3:499.
[51] Herbert LJ, Monaghan M, Cogen F, Streisand R. The impact of parents' sleep quality and hypoglycemia worry on diabetes self-efficacy. Behav Sleep Med 2015;13(4):308–23.
[52] Schierloh U, Aguayo GA, Fichelle M, et al. Effect of predicted low suspend pump treatment on improving glycaemic control and quality of sleep in children with type 1 diabetes and their caregivers: The QUEST randomized crossover study. Trials 2018;19(1):665.
[53] Sharifi A, De Bock MI, Jayawardene D, et al. Glycemia, treatment satisfaction, cognition, and sleep quality in adults and adolescents with type 1 diabetes when using a closed-loop system overnight versus sensor-augmented pump with low-glucose suspend function: A randomized crossover study. DiabetesTechnol Ther 2016;18(12):772–83.
[54] McCarthy MM, Grey M. Type 1 diabetes self-management from emerging adulthood through older adulthood. Diabetes Care 2018;41(8):1608–14.