Obesity Facts

Research Article

Obes Facts 2023;16:69–81
DOI: 10.1159/000527838

Received: May 24, 2022
Accepted: October 24, 2022
Published online: November 1, 2022

Early Time-Restricted Eating Reduces Weight and Improves Glycemic Response in Young Adults: A Pre-Post Single-Arm Intervention Study

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Keywords
Body composition · Cardiometabolic risk · Diet · Obesity management · Weight loss

Abstract

Introduction: Time-restricted eating (TRE) has cardiometabolic health benefits by optimizing circadian rhythms. However, limited data are available on the effect of early TRE in young adults. The objective of this pre-post single-arm trial was to test the effect of TRE on body composition and cardiometabolic risk factors and to evaluate changes in meal and sleep timing by TRE among young adults with typically late bedtime. ***Methods:*** This 4-week intervention was conducted in healthy young adults aged 18–39 years. Dietary records with time logs were collected before and during the intervention, and nutrient intake and meal timing were evaluated. Snack packages containing 20 g of protein per day were provided weekly. Body composition was measured weekly using bioelectrical impedance analysis. Blood samples were collected before and after the intervention, and cardiometabolic parameters were evaluated. ***Results:*** Of the 36 screened participants, 34 completed the study (completion rate 94.4%). The average age was 23.4 ± 2.9 years with 64.7% female. The mean wake-up time and bedtime were 09:16 ± 01:26 and 01:51 ± 01:39 with average sleep duration of 7.4 ± 1.4 h. Body weight and fat mass, excluding muscle mass, were significantly reduced over 4 weeks compared to baseline only in the early TRE group starting before noon. The early TRE group also showed significantly reduced fasting glucose, fasting insulin, and serum triglyceride (TG) levels after 4 weeks. However, the late TRE group starting after noon showed no significant changes except a reduced TG level. The meal timing was changed by TRE, where the first meal was delayed and the last meal was shifted. Neither sleep duration nor timing was significantly changed by TRE. Energy intakes were not different, but protein intake increased from 19.2% to 22.6% due to snack packages during intervention. However, no significant correlation between nutrient intakes and body composition changes was found. There were no adverse events related to study participation. ***Conclusions:*** An early TRE regimen may be a feasible and effective strategy to manage body composition and cardiometabolic risk factors in young adults without altering the sleep-wake cycle.

Trial registration: The study was registered with the Clinical Research Information Service (CRIS.nih.go.kr), identifier: KCT0006443.

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Introduction

Time-restricted eating (TRE) is a type of intermittent fasting that has gained popularity as a simple dietary strategy for weight loss [1, 2]. TRE involves confining eating to a specific number of hours per day, without the need to count calories or monitor food intake, which leads to an extension of the overnight fasting period by 14–20 h [3, 4]. While animal trials have already provided compelling evidence of the effectiveness of TRE [5, 6], there is emerging evidence in humans that intermittent fasting and TRE can yield mild to moderate weight loss and also benefit cardiometabolic health by improving glucose or lipid metabolism, although the findings are variable [2, 7].

The key putative mechanism underlying TRE is optimization of the circadian rhythm. Misalignment between food intake and the circadian rhythm can contribute to disruption of the latter, which results in cardiometabolic disorders [4]. Late-night eating and high-calorie evening meals are associated with cardiometabolic risk factors, while eating more calories in the morning was reported to be associated with higher insulin sensitivity [8, 9]. As TRE shortens the eating period, it influences late-night eating and energy intake in the evening.

Early TRE (*e*TRE) is regarded as optimal to maximize metabolic benefits. Several studies reported that *e*TRE (eating window starts as early as 08:00) improved insulin sensitivity, lipid metabolism, and circadian gene expression [10–12]. However, this schedule is socially challenging for youth and young adults. In modern society, young adults commonly experience circadian changes (i.e., a shift from morning to evening) due to exposure to artificial light at night as well as continuous access to food throughout the day. More screen time is associated with poorer sleep outcomes and delayed sleep-wake behavior is commonly reported among youth and adolescents worldwide [13]. According to a large-scale survey, younger adults often have an evening-dominant energy intake pattern [14].

Several studies have reported that people with an evening chronotype have more eating occasions and poorer eating habits, where these factors are associated with metabolic disorders due to their effects on insulin sensitivity and satiety hormone levels [14–16]. With regard to body weight, young adolescents and college freshmen with evening chronotypes showed higher body mass index (BMI) than those with morning chronotypes [17, 18].

In weight loss interventions, it is important to improve body composition that specifically target a decrease in fat mass while maintaining lean body mass, due to the loss of lean body mass having negative health consequences that include lowered resting energy expenditure or an increased risk of sarcopenia [19, 20]. TRE has been reported to reduce body weight by primarily decreasing fat mass [21, 22], but some studies have also reported a significant reduction in lean body mass [3, 23]. High-protein diets have been suggested as a strategy to preserve lean body mass during a period of weight loss [19]. A 12-week intervention of intermittent fasting, resistance training, and a prescribed daily protein intake of more than 1.4 g per kg body weight has been shown to significantly reduce body weight and fat mass while also increasing lean body mass [24].

In this context, it is necessary to elucidate the impact of TRE in young adults with evening-dominant lifestyles, along with supplementation of high-protein snacks. As meal timing and sleep are key cues for circadian alignment, this study was aimed to explore the effects of TRE on body composition, cardiovascular risk factors, and changes in sleep and meal timing in healthy young adults with a delayed sleep cycle.

Materials and Methods

Study Design and Participants

We performed a 4-week single-arm intervention study with 8-h TRE. In the pre-intervention period, volunteers were instructed to complete 3-day dietary records. All participants underwent a baseline assessment, which included general questionnaires, body measurements, and blood collection. Participants were asked to select the eating window that best fit their lifestyle and were required to remain in their assigned eating schedule group throughout the intervention. Although calories were not counted, weekly snack packages that included high-protein foods such as high-protein bars (for a daily protein intake of 20 g) were provided to supplement their diets and minimize muscle loss. During the intervention, a daily dietary record was completed (28 days in total; sleep and meal times were also recorded). Body composition was measured weekly, and blood collection was performed again after 4 weeks (shown in Fig. 1).

The participants were recruited between July 2021 and August 2021 through an online network and notices placed around the campus of the Catholic University of Korea. The inclusion criteria were as follows: healthy young adults aged 18–39 years; no metabolic or other diseases, such as depression; no food allergies, including soybeans and nuts; and <10% weight change in the previous month. Forty-one participants were recruited, but 2 with scheduling conflicts, 2 receiving treatment for other diseases, and 1 above the age cutoff were excluded. After screening, 36 participants began a 4-week TRE intervention; 2 dropped out of the study due to schedule conflicts or loss of contact. Therefore, 34 participants finally completed the intervention (shown in online suppl. Fig. 1; see www.karger.com/doi/10.1159/000527838 for all online suppl. material).

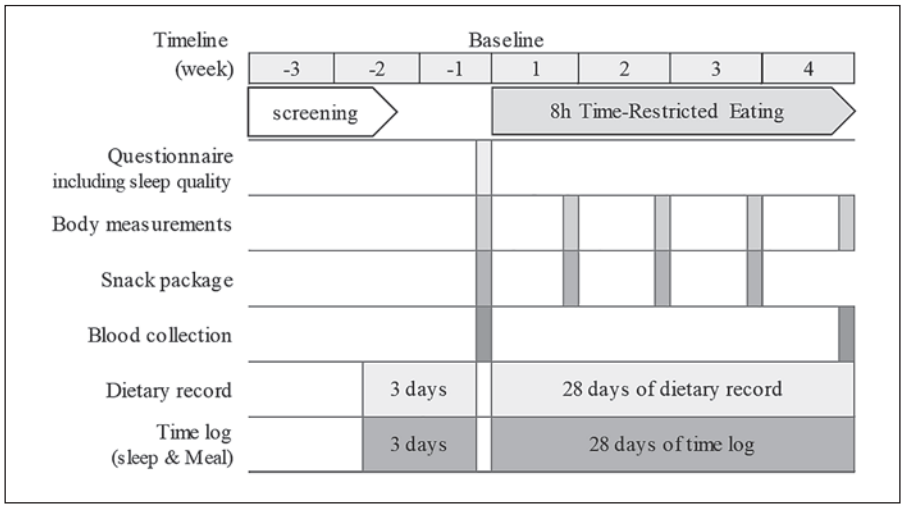

Fig. 1. Study design of 4-week intervention with 8-h time-restricted eating.

All participants received detailed information about the purpose and process of the study. They provided written informed consent and received a stipend for their participation. All procedures were approved by the Institutional Review Board of the Catholic University of Korea (No. 1040395-202106-05), and the study was registered with the Clinical Research Information Service (KCT0006443), which is an online registration system for clinical trials and clinical research conducted in Korea, and on the WHO International Clinical Trial Registry Platform.

Early and Late TRE Group

To ensure compliance, the eating window was chosen by participants at baseline, and the starting time of the eating window varied by each participant (shown in online suppl. Fig. 2). The majority of participants chose to start eating before noon, but 38.2% (13 participants) chose to start eating from noon onward. According to the eating window, participants were divided into two groups: *e*TRE and late TRE (*l*TRE). There was no difference in age and sex distribution by groups (Table 1).

Body Measurements

Weight, body composition, and waist circumference were measured weekly in a fasting state after 8 h of fasting. Height was assessed only at baseline using an extensometer (DS-102; Dong Sahn Jenix Co., Ltd., Seoul, South Korea). Weight and body composition were measured by a bioelectrical impedance method (InBody 370S; Inbody Co., Seoul, South Korea), while the subjects wore light clothes and no shoes. BMI was calculated as weight/height^2 (kg/m^2), and muscle mass (kg), body fat mass (kg), and percent body fat (%) were determined. Waist circumference was measured to the nearest 0.1 cm using a flexible anthropometric tape in a horizontal plane around the highest point of the hip bone.

Cardiometabolic Risk Factors

Samples of whole blood were collected into 5-mL tubes at baseline and after the intervention, at the Catholic University of Korea Bucheon St. Mary's Hospital. About 30 min after collection, the blood samples were centrifuged, and the SST tubes were transferred to the Global Clinical Central Lab (GC Labs, Gyeonggi-do, South Korea) for analysis. Laboratory analysis included fasting glucose, insulin, total cholesterol (TC), high-density lipoprotein cholesterol (HDL cholesterol), low-density lipoprotein cholesterol (LDL cholesterol), and triglycerides (TG). Fasting glucose was analyzed by UV spectrophotometry, insulin was analyzed by electrochemiluminescence immunoassay, and serum lipids (TC, HDL cholesterol, LDL cholesterol, and TG) were analyzed by colorimetry (Cobas 8,000; Roche, Mannheim, Germany). Insulin resistance was evaluated using the Homeostasis Model Assessment of Insulin Resistance (HOMA-IR), calculated using the formula: fasting glucose (mg/dL) × fasting insulin (μU/mL)/405 [25]. Blood pressure was measured three times at 1-min intervals using an automatic electronic blood pressure monitor (HEM-7156; Omron Healthcare Co., Ltd., Kyoto, Japan), and the average values were used for the analysis.

Dietary Assessment and Meal Timing

To compare dietary intake before and during the intervention, participants were asked to record their daily diet on 3 nonconsecutive days (2 weekdays and 1 weekend day) in the week prior to the intervention. The daily dietary records were collected via a mobile messaging app and reviewed by staff for accuracy and completeness. Participants were instructed to indicate the name of each food or drink consumed and the quantity and preparation process, if possible. Meals were classified as breakfast, lunch, or dinner, and snacks between meals were also reported. Daily dietary records were accompanied by a time log of all meals.

"Meal timing" was computed based on the starting time of the first and last meals. The time of the first snack of the day was also recorded. Eating occasions were counted, including snacks. "Meal proportion" refers to the percentage of the daily total energy intake of each meal. All dietary data were entered and nutrient intakes were analyzed using the Diet Evaluation System program developed by the Human Nutrition Research Institute of Seoul National University.

Sleep and Circadian Variables

Sleep data were recorded in the daily time log. Sleep duration was calculated using the bedtime and wake-up time. For investiga-

Table 1. General characteristics of the participants at baseline

	Total (n = 34)	*e*TRE (n = 21)	*l*TRE (n = 13)	p value[1]
Eating window, *n* (%) (starting time)				
<10:00	4 (11.8)	4 (19.1)		
10:00–11:00	8 (23.5)	8 (38.1)		
11:00–12:00	9 (26.5)	9 (42.9)		
12:00–13:00	9 (26.5)		9 (69.2)	
≤13:00	4 (11.8)		4 (30.8)	
Age, years	23.4±2.9	23.7±3.4	22.9±1.9	0.6321
Female sex, *n* (%)	22 (64.7)	13 (61.9)	9 (69.2)	0.6640
BMI, kg/m^2	23.6±4.3	23.5±3.8	23.7±5.1	0.7363
Sleep duration, h	7.4±1.4	7.4±1.1	7.4±1.9	1.0000
Wake-up time, hh:mm	09:16±01:26	09:00±01:22	09:42±01:30	0.2214
Bedtime, hh:mm	01:51±01:39	01:34±01:33	02:19±01:46	0.3038
Habitual sleep efficiency, *n* (%)				
>85%	22 (64.7)	16 (76.2)	6 (46.2)	0.1902
75–84%	8 (23.5)	3 (14.3)	5 (38.5)	
65–74%	3 (8.8)	2 (9.5)	1 (7.7)	
<65%	1 (2.9)	0 (0.0)	1 (7.7)	
Subjective sleep quality, *n* (%)				
Very good	5 (14.7)	5 (23.8)	0 (0.0)	0.1131
Good	20 (58.8)	10 (47.6)	10 (76.9)	
Poor	9 (26.5)	6 (28.6)	3 (23.1)	
Sleep quality[2], *n* (%)				
Optimal (1–5)	10 (29.4)	8 (38.1)	2 (15.4)	0.3686
Borderline (6–7)	11 (32.4)	6 (28.6)	5 (38.5)	
Poor (≥8)	13 (38.2)	7 (33.3)	6 (46.2)	
Alcohol consumption, *n* (%)				
Yes	23 (67.7)	10 (47.6)	13 (100.0)	**0.0015**
No	11 (32.4)	11 (52.4)	0 (0.0)	
Current smoker, *n* (%)				
Yes	7 (20.6)	4 (19.1)	3 (23.1)	0.7777
No	27 (79.4)	17 (81.0)	10 (76.9)	
Physical activity, *n* (%)				
High	9 (26.5)	5 (23.8)	4 (30.8)	0.7427
Moderate	21 (61.8)	14 (66.7)	7 (53.9)	
Low	4 (11.8)	2 (9.5)	2 (15.4)	

All values are presented as mean ± SD or *n* (%). BMI, body mass index; *e*TRE, early TRE (starting before noon); *l*TRE, late TRE (starting after noon); SD, standard deviation. [1] p values for group comparisons by the χ^2 test for categorical variables and the Wilcoxon rank sum test for continuous variables. [2] Sleep quality was assessed by the Pittsburgh Sleep Quality Index.

tion of chronotype, mid-sleep was computed as the average midpoint between wake-up and bedtime on workdays and free days. Chronotype refers to sleep phase rather than duration [26].

Sleep quality was assessed by a self-rated questionnaire of the Pittsburgh Sleep Quality Index (PSQI) at baseline [27, 28]. Among the seven PSQI factors, the following six were recorded for the following factors (the factor pertaining to medications for depression was omitted because such individuals were excluded during screening): habitual sleep efficiency, sleep latency, sleep duration, sleep disturbance, subjective sleep quality, and daytime dysfunction. In scoring the PSQI, overall sleep quality was calculated by summing all factors [28] and classified as optimal (1–5), borderline (6–7), or poor (≥8) [27, 29].

Other Covariates

Participants were asked to complete a questionnaire on general characteristics, including lifestyle factors. Participants who indicated that they smoked everyday were classified as current smokers, and those who consumed alcohol more than once a month were classified as drinkers. Physical activity was categorized as low, moderate, or high intensity based on the International Physical Activity Questionnaire (IPAQ) [30]. MET-min/week was calculated according to the formula: MET-min/week = MET level × min of activity × events per week (walking, 3.3 METs; moderate activity, 4.0 METs; intense activity, 8.0 METs). High intensity was defined as at least 1,500 MET-min/week of exercise with at least 3 days of intense physical activity per week or at least 3,000 MET-

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Table 2. Body composition and cardiometabolic parameters in the pre- and post-intervention periods: results of the 4-week, 8-h TRE intervention for healthy young adults

	Total (n = 34)		p value[1]	eTRE (n = 21)		p value[2]	lTRE (n = 13)		p value[2]
	pre-intervention	post-intervention		pre-intervention	post-intervention		pre-intervention	post-intervention	
Body composition									
Body weight, kg	67.2±18.3	66.1±17.9	**0.0003**	66.9±15.5	65.5±14.8	**<0.0001**	67.7±22.8	67.1±22.7	0.2109
BMI, kg/m^2	23.6±4.3	23.2±4.1	**0.0005**	23.5±3.8	23.0±3.5	**0.0004**	23.7±5.1	23.5±5.1	0.3008
Waist circumference, cm	76.7±13.0	75.1±11.9	**0.0007**	76.2±10.7	74.4±9.4	**0.0043**	77.6±16.6	76.1±15.5	**0.0479**
Muscle mass, kg	26.3±8.2	26.1±8.1	0.0716	26.6±7.8	26.4±7.7	0.0844	25.8±9.1	25.7±9.1	0.5757
Fat mass, kg	19.5±7.4	18.8±7.3	**0.0001**	18.7±6.3	17.8±6.0	**0.0002**	20.9±9.0	20.4±9.0	0.1421
Body fat percentage, %	29.0±6.8	28.4±7.1	**0.0062**	28.1±7.3	27.4±7.5	**0.0132**	30.3±6.0	30.0±6.2	0.2095
Cardiometabolic parameters									
Insulin, μU/mL	10.8±5.2	10.6±12.0	0.9115	10.9±5.5	8.6±4.7	**0.0286**	10.6±4.7	13.9±18.4	0.4043
Fasting glucose, mg/dL	90.0±8.1	87.1±7.1	**0.0414**	89.8±9.4	86.1±6.5	**0.0131**	90.3±5.7	88.7±7.9	0.6069
HOMA-IR	2.4±1.3	2.4±3.2	0.9197	2.5±1.4	1.8±1.1	**0.0103**	2.4±1.2	3.3±5.0	0.3757
TC, mg/dL	188.1±23.1	185.0±24.9	0.2287	184.4±22.9	181.1±23.4	0.1693	193.9±23.0	191.2±27.0	0.5974
LDL cholesterol, mg/dL	104.2±20.3	109.5±23.3	**0.0282**	101.3±18.6	107.3±22.0	**0.0219**	108.8±22.7	113.1±25.6	0.5557
TG, mg/dL	100.6±65.2	79.3±46.2	**0.0223**	98.4±79.4	74.8±44.3	**0.0243**	104.2±34.0	86.5±50.2	**0.0203**
HDL cholesterol, mg/dL	63.2±15.9	59.3±13.7	**0.0014**	63.1±16.9	58.9±13.7	**0.0123**	63.3±14.6	59.9±14.3	0.0706
Systolic blood pressure, mm Hg/dL	105.5±12.0	103.6±10.2	0.1555	104.0±11.1	102.4±9.9	0.4684	107.9±13.4	105.4±10.9	0.4143
Diastolic blood pressure, mm Hg/dL	72.9±6.9	71.9±5.5	0.2810	71.2±5.8	70.8±5.3	0.9733	75.7±7.7	73.6±5.5	0.1272

All values are presented as mean ± SD or n (%). eTRE, early TRE (starting before noon); HDL, high-density lipoprotein; HOMA-IR, Homeostasis Model Assessment of Insulin Resistance; lTRE, late TRE (starting after noon); LDL, low-density lipoprotein; SD, standard deviation; TG, triglyceride. [1] p values between pre- and post-intervention periods using the paired t test. [2] p values between pre- and post-intervention periods using the Wilcoxon signed rank test.

min/week of exercise in any combination of intensity for more than 7 days a week. Moderate intensity was defined as walking on more than 5 days a week or at least 600 MET-min/week of exercise (any intensity). Low intensity was defined as no high- or moderate-intensity exercise.

Statistical Analysis

The basic characteristics are presented as a number (*n*) and percentage (%); continuous variables are presented as mean ± standard deviation. The χ^2 test was used for analysis of categorical variables, and the Wilcoxon rank sum test was used to compare continuous variables between groups. Within individuals, pre-intervention and intervention period data were compared using the paired *t* test. The Wilcoxon signed rank test was used by groups. Spearman's partial correlation analysis was performed with adjustments for age, sex, alcohol consumption, smoking status, and physical activity. All data were analyzed using SAS 9.4 software (SAS Institute Inc., Cary, NC, USA). In all analyses, $p < 0.05$ was taken to indicate statistical significance.

Results

The general characteristics of the 34 participants are presented in Table 1. The mean age was 23.4 ± 2.9 years, the proportion of women was 64.7%, and the mean BMI was 23.6 ± 4.3 kg/m^2. The average wake-up and bedtimes at baseline were 09:16 ± 01:26 and 01:51 ± 01:39 (hh:mm), respectively. The mean sleep duration was 7.3 ± 1.5 h. Although 73.5% of the participants reported good or very good subjective sleep quality, 38.2% had poor overall sleep quality in the Pittsburgh Sleep Quality Index. Other components of sleep quality were presented in online supplementary Table 1. With regard to lifestyle characteristics, 67.7% of participants reported drinking alcohol, 20.6% were current smokers, and 26.5% had high levels of physical activity.

The *e*TRE group starting the eating window before 12:00 showed no differences in age, BMI, sleeping time, or all components of the sleep quality index with *l*TRE groups. However, all subjects in the *l*TRE group reported drinking alcohol, compared to only 47.6% of subjects in the *e*TRE group.

Effects of TRE on Body Composition and Cardiometabolic Parameters

Pre- and post-intervention body composition and cardiometabolic parameters are compared in Table 2. With the exception of muscle mass, the post-intervention body composition measures were significantly decreased compared to the pre-intervention values only in the *e*TRE group.

With regard to cardiometabolic parameters, the post-intervention fasting glucose, serum TG, and HDL cholesterol levels were significantly decreased, while LDL cholesterol was significantly increased compared to the pre-intervention levels. The *e*TRE group showed significant improvements in glucose and insulin parameters; the *l*TRE group showed no such improvements. Serum TG levels were significantly decreased in both groups, but only the *e*TRE group showed increased post-intervention LDL cholesterol levels and decreased HDL cholesterol levels. There were no differences in systolic or diastolic blood pressure pre-versus post-intervention or between eating window groups.

As shown in Figure 2, the *e*TRE and *l*TRE groups showed different weekly changes in body composition measures during the 4-week intervention. In the *e*TRE group, body weight showed gradual and significant decreases of −0.9, −1.0, −1.3, and −1.4 kg in weeks 1–4, respectively, compared to the baseline. Similar to body weight change, fat mass also gradually and significantly decreased by −0.7 and −0.9 kg, respectively, in weeks 3 and 4. On the other hand, muscle mass decreased slightly by −0.4 kg in the first 2 weeks but increased in the last 2 weeks such that it was 0.3 kg lower than at baseline. The *l*TRE group showed no significant changes in any measures of body composition by week.

Changes in Sleep and Meal Variables

Changes in sleep and meal timing are presented in Table 3. The sleep duration was not significantly different between the pre-intervention and intervention periods (7.4 ± 1.4 and 7.5 ± 0.8 h, respectively). The wake-up time was 09:16 ± 01:26 (hh:mm) at baseline and 09:13 ± 01:06 (hh:mm) during the intervention, which was not significantly different. Bedtime was 01:51 ± 01:39 (hh:mm) at baseline and shifted to a slightly earlier time of 01:40 ± 01:09 (hh:mm) during the intervention; the difference was not significant. According to the eating window groups, there was no change in sleep duration or sleep timing before intervention and during intervention. Thus, the 4-week TRE intervention had no effect on sleep duration or sleep cycle.

On the other hand, the meal timings differed significantly between the pre-intervention and intervention periods. The first meal started at 10:29 ± 02:24 (hh:mm) at baseline and was significantly delayed to 11:51 ± 01:21 (hh:mm) during the intervention. The last meal started at 18:30 ± 01:32 (hh:mm) in the pre-intervention period and was significantly earlier at 17:43 ± 01:11 (hh:mm) during the intervention. These changes were more evident in the

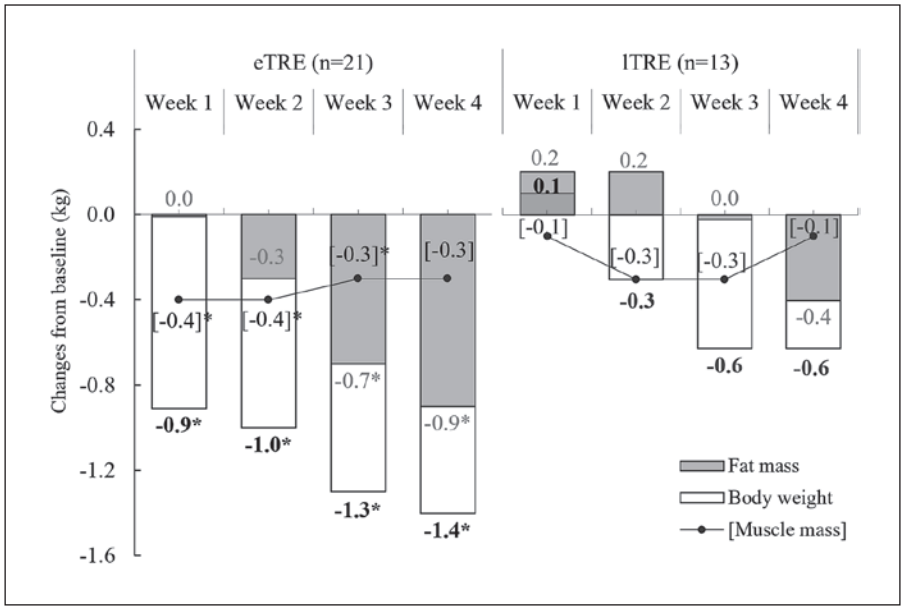

Fig. 2. Changes in body composition by week during the 4-week, 8-h TRE intervention. *$p < 0.05$ was from the Wilcoxon signed rank test for individual changes between each week and baseline.

*e*TRE than the *l*TRE group. The *e*TRE group showed significantly shifted times in the first and last meals, whereas only the first meal timing was significantly delayed in the *l*TRE group.

In contrast to meal timings, TRE had no significant effect on the average number of eating occasions (3.4 and 3.3 per day in the pre-intervention and intervention periods, respectively). There was also no difference in the number of eating occasions in eating window groups. TRE altered meal proportions. While the proportion of energy intake at breakfast had a tendency to reduce from 16.3 ± 12.9% in the pre-intervention period to 12.8 ± 12.2% during the intervention, the proportion of energy intake from lunch increased significantly from 30.8 ± 10.3% in the pre-intervention period to 35.0 ± 7.6% during the intervention. The proportions of energy from snacks and dinner were not different between the pre-intervention and intervention periods. The proportion of energy was not much differed by meal in the *e*TRE group, except for a slight reduction from dinner. However, the *l*TRE group showed the proportion of energy significantly reduced from breakfast and increased from lunch.

Changes in Nutrient Intake

As shown in Table 4, there were no significant differences in energy intake between the pre-intervention and intervention periods. Carbohydrate and fat intakes were not different between the pre-intervention and intervention periods, but the proportion of energy from carbohydrates was 50.0% ± 7.4% in the pre-intervention period and decreased significantly to 44.8% ± 2.9% during the intervention. Protein accounted for 19.2% ± 4.5% of energy at baseline; this increased significantly to 22.6% ± 2.9% during the intervention due to the provision of the snack packages. Dietary sugar and saturated fat intakes were not different between baseline and during the intervention. These changes in nutrient intake between pre- and during intervention were similar in both the early and late TRE groups.

Correlations of Meal and Sleep Variables with Changes in Body Composition

Table 5 shows the correlations of sleep and meal variables with the changes in body composition over the 4-week intervention period. After adjusting for potential confounders, sleep-related variables including sleep quality using PSQI showed no relations with changes in body weight or muscle mass. However, the fat mass change was significantly positively related with bedtime and mid-sleep. Meal timings were not correlated with changes in any body composition measures. The average intakes of all nutrients, including protein, during the intervention were not correlated with any of the body composition measures.

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Table 3. The change of sleep and meal timing related variables via 4 weeks intervention with 8-h TRE in healthy young adults

	Total subjects (n = 34)		p value[1]	eTRE (n = 21)		p value[2]	lTRE (n = 13)		p value[2]
	pre-intervention	during intervention		pre-intervention	during intervention		pre-intervention	during intervention	
Sleep duration, h	7.4±1.4	7.5±0.8	0.5733	7.4±1.1	7.4±0.7	0.9333	7.4±1.9	7.8±0.9	0.5417
Sleep timing, hh:mm									
Wake-up	09:16±01:26	09:13±01:06	0.7831	09:00±01:22	08:50±00:59	0.3698	09:42±01:30	09:50±01:02	0.9460
Bedtime	01:51±01:39	01:40±01:09	0.2558	01:34±01:33	01:26±01:07	0.4274	02:19±01:46	02:04±01:10	0.5879
Mid-sleep of free days	05:53±01:41	05:41±01:09	0.2692	05:33±01:49	05:22±01:07	0.7246	06:27±01:19	06:11±01:04	0.5417
Mid-sleep of workdays	05:24±01:23	05:21±01:05	0.7301	05:09±01:16	05:02±01:01	0.4477	05:47±01:33	05:51±01:03	0.8394
Meal timing, hh:mm									
First meal	10:29±02:24	11:51±01:21	**0.0013**	10:02±02:17	11:08±01:09	**0.0258**	11:13±02:31	13:01±00:42	**0.0105**
Last meal	18:30±01:32	17:43±01:11	**0.0120**	18:12±01:28	17:03±00:57	**0.0025**	18:58±01:35	18:47±00:35	0.4143
Eating occasion, n per day	3.4±0.9	3.3±0.6	0.5035	3.5±1.0	3.3±0.6	0.7500	3.2±0.7	3.2±0.5	0.8926
Meal	2.2±0.4	2.1±0.3	0.1333	2.3±0.4	2.2±0.4	**0.0154**	2.0±0.4	2.0±0.1	0.8350
Snack	1.2±0.7	1.2±0.6	0.9917	1.2±0.8	1.1±0.6	0.9866	1.2±0.6	1.3±0.4	1.0000
Meal proportion, % E									
Breakfast	16.3±12.9	12.8±12.2	0.1828	17.6±13.8	14.6±14.5	0.2774	14.3±11.5	0.2±0.4	**0.0029**
Lunch	30.8±10.3	35.0±7.6	**0.0447**	32.8±11.0	36.7±13.3	0.8538	27.5±8.6	41.6±5.0	**0.0017**
Dinner	37.3±12.8	33.7±7.6	0.1013	35.6±11.9	34.2±10.4	**0.0258**	40.2±14.0	40.9±4.1	0.8394
Snack	15.6±11.4	18.5±6.4	0.1119	14.1±11.8	14.6±7.7	0.0995	18.0±10.6	17.3±5.9	0.3396

Values are presented as mean ± SD. SD, standard deviation; eTRE, early TRE (starting before noon); lTRE late TRE (starting after noon). [1] Individual difference was tested between pre and during intervention using the paired t-test in total subjects. [2] Individual difference was tested between pre and during intervention using the Wilcoxon signed rank test in each group.

Table 4. Changes in nutrient intake by 4-week intervention with 8-h TRE in healthy young adults

	Total subjects (n = 34)		p value[1]	eTRE (n = 21)		p value[2]	lTRE (n = 13)		p value[2]
	pre-intervention	during intervention		pre-intervention	during intervention		pre-intervention	during intervention	
Energy, kcal	1,655.2±485.5	1,645.0±321.8	0.8932	1,630.1±503.6	1,570.1±314.9	0.6995	1,695.7±471.8	1,766.0±306.4	0.4973
Carbohydrate, g	198.4±58.9	179.7±35.7	0.0540	195.3±64.9	172.0±36.3	0.1074	203.3±49.7	192.2±32.0	0.4548
Dietary sugar, g	43.8±24.4	40.7±13.3	0.3116	40.8±25.2	38.9±13.1	0.8538	48.6±23.3	43.7±13.5	0.5417
Protein, g	75.7±25.3	90.0±18.0	**0.0011**	75.9±24.8	87.8±19.5	**0.0258**	75.3±27.1	93.7±15.3	**0.0266**
Protein, g/kg	1.1±0.3	1.4±0.3	**0.0002**	1.1±0.3	1.4±0.2	**0.0103**	1.2±0.4	1.5±0.3	**0.0215**
Fat, g	56.4±25.3	58.2±12.6	0.6700	55.9±24.9	56.8±12.6	0.8275	57.0±27.0	60.4±12.7	0.4143
Saturated fat, g	19.6±10.0	20.2±4.9	0.6936	18.9±10.1	19.5±5.0	0.556	20.6±10.1	21.4±4.7	0.4973
Energy proportion (%)									
Energy for EER	75.2±20.7	74.7±12.3	0.8845	73.4±21.9	70.8±12.6	0.7500	78.0±19.2	80.9±9.1	0.4973
Carbohydrate	50.0±7.4	44.8±2.9	**0.0003**	49.4±7.7	44.4±3.2	**0.0053**	51.1±7.1	45.6±2.5	**0.0327**
Dietary sugar	10.8±4.9	10.3±3.2	0.3999	10.1±5.2	10.1±3.3	0.5789	11.9±4.3	10.5±3.2	0.1909
Protein	19.2±4.5	22.6±2.9	**<0.0001**	19.6±4.4	22.7±2.8	**0.0018**	18.6±4.7	22.4±3.0	**0.0105**
Fat	30.7±6.6	32.6±2.9	0.1284	31.0±5.4	32.9±3.2	0.1434	30.2±8.3	32.0±2.4	0.2734
Saturated fat	10.5±2.9	11.3±1.6	0.1314	10.3±2.5	11.3±1.7	0.2123	11.0±3.6	11.4±1.3	0.5879

Values are presented as mean ± SD. EER, estimated energy requirement; eTRE, early TRE (starting before noon); lTRE late TRE (starting after noon). [1] Individual difference was tested between pre and during intervention using the paired t test in total subjects. [2] Individual difference was tested between pre and during intervention using the Wilcoxon signed rank test in each group.

Discussion

This study was performed to examine the effects of 4 weeks of TRE on body composition and cardiometabolic risk factors in healthy young adults with a delayed sleep-wake cycle. The results showed that 8-h TRE produced significant weight loss through a reduction of fat mass without any reduction of muscle mass, as well as an improved glycemic response and reduced blood TG levels. However, these benefits were evident only in those whose eating window started before noon.

Our participants were mostly college students with considerably delayed bedtimes (01:40 ± 01:09 (hh:mm) during the intervention). This tendency to delay bedtimes and extend rise times has been reported previously in large-scale surveys of adolescents [31] and college students [29]. The late chronotype can be determined based on mid-sleep on free days later than 05:30 (hh:mm) [32]; the average mid-sleep time on free days was 05:23 in the *e*TRE group and 06:11 in the *l*TRE group, indicating that most participants had a late chronotype. The late chronotype is associated with increased BMI, poorer dietary behaviors, and a greater desire for high-fat foods [17, 18]. We also found that the fat mass change over 4 weeks had a significant positive relationship with bedtime. Participants with later bedtimes were statistically more likely to have less fat loss compared to participants with earlier bedtimes. As bedtime was measured by a 28-day daily log, it reflects the usual sleep time of the participants.

Interestingly, although sleep is considered a potential mediator of the relationship between TRE and cardiometabolic risk factors, we found that TRE did not change the sleep cycle. This was consistent with a previous study showing that 12 weeks of TRE did not alter sleep quality or duration in subjects with obesity [33]. It indicates that delayed bedtime would be a potential mediator rather than sleep quality or duration in young adults.

The primary findings of this study were that 8-h TRE with an eating window starting before noon was effective for managing body weight, blood glucose, and lipid profiles without altering the sleep cycle, as well as for restricting energy intake. *e*TRE is considered to lead to better health outcomes, but limited data are available and the findings reported to date have been inconclusive. A study comparing *e*TRE (from 08:00 to 14:00) with a control schedule (eating from 08:00 to 20:00) showed that the former regimen improved insulin sensitivity, blood pressure, and oxidative stress [10]. Another study comparing *e*TRE (08:00–17:00) with delayed TRE (12:00–21:00) showed that both regimens improved glucose tolerance

Table 5. Correlations of sleep and meal timing variables during the intervention period with changes in body composition over 4 weeks

	Body composition change, week 4–week 0			
	body weight, kg	fat mass, kg	muscle mass, kg	BMI, kg/m^2
Sleep variables				
Sleep duration, h	−0.131	−0.195	−0.209	−0.194
Wake-up time, hh:mm	−0.034	0.314	−0.292	−0.075
Bedtime, hh:mm	0.072	**0.379***	−0.111	0.096
Mid-sleep of free day	−0.035	0.212	−0.156	−0.014
Mid-sleep of weekday	0.012	**0.371***	−0.246	0.012
Sleep quality (PSQI)	0.112	0.354	−0.054	0.199
Meal timing variables				
First meal, hh:mm	0.274	0.140	0.098	0.330
Last meal, hh:mm	0.229	0.013	0.110	0.293
Nutrient intake				
Energy, kcal	0.307	0.255	0.300	0.211
Carbohydrate, %	0.124	0.305	−0.015	0.114
Dietary sugar, %	−0.310	−0.053	−0.152	−0.293
Protein, %	−0.256	−0.198	−0.228	−0.338
Protein, g	0.044	0.060	0.056	−0.116
Fat, %	0.171	−0.058	0.292	0.235
Saturated fat, %	0.166	0.008	0.277	0.275

Partial correlations were adjusted for age, sex, alcohol drinking, smoking, and physical activity. Values are Spearman's correlation coefficients. * $p < 0.05$. PSQI, Pittsburgh Sleep Quality Index.

[34]. However, both studies were performed in middle-aged adults with overweight or prediabetes, and the eating window started at 08:00, which is not practical for young adults with a delayed sleep-wake cycle.

Two other studies compared the effects of TRE with different timings. The first study showed no significant differences in obesity-related outcomes between early (before 09:47), intermediate (09:47–10:50), and late (after 10:50) eating windows [35], while the second showed greater reductions of body mass and fat mass in the *e*TRE (06:00–15:00) than the midday TRE (11:00–20:00) and control groups (ad libitum) [22].

Compared to previous studies, the eating window of the *e*TRE group in this study was not predetermined. Almost 80% of participants had an eating window start time between 10:00 and noon, with a wide range of start times (08:00 to 12:00). The observed benefits seen despite this wide range have been because the self-selected window led to high adherence and refraining from late-night eating (after 20:00) has greater benefit for managing cardiometabolic risk factors than beginning to eat as early as 08:00. Late-night eating and large evening meals are associated with undesirable health outcomes, such as a higher risk of metabolic syndrome [36] and higher diastolic blood pressure [8]. In addition, a large-scale study revealed that hyperglycemia was associated with late-night eating alone but not breakfast skipping alone [37]. Taken together, the present study suggests that, for young adults with a delayed sleep cycle, refraining from late-night eating may be a more effective way to manage cardiometabolic risk factors than having breakfast as early as 08:00. Further studies are needed to determine the optimal eating window to maximize the effects of TRE; the sleep-wake cycle should also be taken into consideration.

Our *e*TRE group showed significantly reduced levels of fasting glucose and insulin after the 4-week intervention. This was consistent with a recent systematic review indicating that an *e*TRE regimen had a beneficial effect on fasting glucose and HOMA-IR [38]. Other reviews also reported the modest desirable changes in fasting glucose, fasting insulin, and HOMA-IR with an *e*TRE regimen [2, 7].

Compared to glucose metabolism, the findings regarding plasma lipids are highly variable among studies. A significant reduction of serum TG was seen in both our *e*TRE and *l*TRE groups, along with increased LDL cholesterol and decreased HDL cholesterol. A study of 12-week TRE in adults with metabolic syndrome showed a trend toward significant reductions of TC and LDL cholesterol [39]. Another study of a 5-week *e*TRE intervention showed no changes in HDL cholesterol or LDL choles-

terol levels but increased TG and TC levels [10]. Glucose metabolism is under strong circadian control and plays an important role in pancreatic beta-cell function [40]. Several rate-limiting steps in lipid metabolism were reported to be related to the circadian system in animal studies, but wide interindividual variability was seen in human studies [41]. Despite inconsistency of previous findings in plasma lipids, we found undesirable changes in LDL cholesterol and HDL cholesterol in the *e*TRE group. This could be explained by macronutrient change during intervention. Both groups experienced a decrease in carbohydrate and an increase in protein, along with no change in energy intake. It has been consistently reported that low-carbohydrate diets showed a greater reduction in TG but increased LDL cholesterol [42]. However, the change rates in LDL cholesterol and HDL cholesterol compared to baseline were small at 5.5% and −5.3%, respectively. This indicates that dietary composition should be considered to optimize health benefits even if TRE regimen involves no calorie counting.

Although the TRE regimen does not require participants to count calories or restrict any particular foods, we encouraged participants to consume high-protein foods. A previous study reported a significant decrease in body weight, as well as a reduction in lean mass, in a TRE group in a 12-week trial [43], although other studies reported no reductions in fat-free mass [44] or lean mass [45]. According to meta-analyses, high dietary protein intake and protein supplementation were beneficial in terms of body composition and maintenance of lean mass [46, 47]. The snack packages provided in the present study supplied 20 g of protein daily, which significantly increased dietary protein intake from 19.2% ± 4.5% in the pre-intervention period to 22.6% ± 2.9% during the intervention. However, we did not find any significant relations between dietary protein intake and changes in body composition measures.

We also found no difference in energy intake between the pre-intervention and intervention periods. Several TRE studies reported unintentional reductions in energy intake in the shortened eating window [1, 3, 39]. However, the number of eating occasions was not different between our *e*TRE and *l*TRE groups; two meals and one snack per day were typical in both groups. According to Dong et al., intermittent fasting and caloric restriction share a number of features, although the former is based on synchronization of physiology with the circadian rhythm (which improves metabolic health) [48].

This study had several limitations. First, this was not a randomized controlled trial. We compared outcomes between *e*TRE and *l*TRE groups, but the groups were self-selected. To truly determine the effects of *e*TRE on body weight and cardiometabolic risk factors, future trials should implement a randomized design. Second, this was a single-arm study without a control group, so we cannot exclude the possibility that the observed changes in body composition were due to some other factor(s). However, the primary outcome was changes in cardiometabolic risk factors after the 4-week intervention, so a pre-post study design was adopted. Finally, the small sample size and relatively short-duration of intervention limit the generalizability of the findings, as well as the ability to detect statistical significance. In particular, the smaller sample size of the *l*TRE group than that of the *e*TRE group possibly prevented the results from reaching statistical significance. Further large-scale, long-term studies are needed to confirm our findings.

As well as some limitations, this study also had several strengths. First, daily dietary records with sleep logs were obtained throughout the study period, which allowed for comprehensive evaluation of changes in meal- and sleep-related variables via TRE. In addition, adherence was monitored, and only one participant was lost to follow-up after the TRE intervention began. Second, body composition was measured weekly, which allowed to evaluate trends in body composition over the 4-week intervention.

Conclusion

To our knowledge, this is the first study of TRE in young adults with a delayed sleep-wake cycle. The high level of adherence to TRE and low dropout rate suggest that a self-selected 8-h TRE may be a feasible strategy to manage body weight and cardiometabolic risk factors even for those with a late chronotype without altering the sleep-wake cycle.

Acknowledgments

The authors deeply thank our study participants.

Statement of Ethics

This study protocol was reviewed and approved by the Institutional Review Board of the Catholic University of Korea (1040395-202106-05) and approved by the Clinical Research Information Service (KCT0006443), which is an online registration system for clinical trials and clinical research conducted in Korea, and on the WHO International Clinical Trial Registry Platform. All partici-

pants received detailed information about the purpose and process of the study. They provided written informed consent and received a stipend for their participation.

Conflict of Interest Statement

The authors have no conflicts of interest to declare.

Funding Sources

This research was supported by the National Research Foundation of Korea (NRF), grant funded by the Korean government (NRF-2020R1F1A1049442), and by grants from the Catholic University of Korea (Research Fund 2022).

Author Contributions

YoonJu Song conceptualized the research, interpreted the results, and supervised all procedures with funding acquisition. JinA Kim carried out the study and analyzed data. All the authors were involved in writing the paper and had given final approval of the submitted and published versions.

Data Availability Statement

All data generated or analyzed during this study are included in this article and its online supplementary material. Further inquiries can be directed to the corresponding author.

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