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Original Contribution

The Relationship Between Obesity and Exposure to Light at Night: Cross-Sectional Analyses of Over 100,000 Women in the Breakthrough Generations Study

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There has been a worldwide epidemic of obesity in recent decades. In animal studies, there is convincing evidence that light exposure causes weight gain, even when calorie intake and physical activity are held constant. Disruption of sleep and circadian rhythms by exposure to light at night (LAN) might be one mechanism contributing to the rise in obesity, but it has not been well-investigated in humans. Using multinomial logistic regression, we examined the association between exposure to LAN and obesity in questionnaire data from over 100,000 women in the Breakthrough Generations Study, a cohort study of women aged 16 years or older who were living in the United Kingdom and recruited during 2003–2012. The odds of obesity, measured using body mass index, waist:hip ratio, waist:height ratio, and waist circumference, increased with increasing levels of LAN exposure ($P < 0.001$), even after adjustment for potential confounders such as sleep duration, alcohol intake, physical activity, and current smoking. We found a significant association between LAN exposure and obesity which was not explained by potential confounders we could measure. While the possibility of residual confounding cannot be excluded, the pattern is intriguing, accords with the results of animal experiments, and warrants further investigation.

body mass index; circadian rhythm; light at night; obesity; sleep; sleeping habits

Abbreviations: BMI, body mass index; CI, confidence interval; LAN, light at night; WHR, waist:hip ratio; WHtR, waist:height ratio.

Editor's note: *An invited commentary on this article appears on page 251.*

The prevalence of obesity in developed societies has been increasing for decades, and the obesity epidemic has become one of the most important global public health issues. Much emphasis has been placed upon changing well-documented factors that are known to contribute to weight gain, such as dietary choices and physical activity levels (1, 2). However, the number of overweight and obese adults and children has continued to increase (3), and the potential effects of other factors are now also being considered (1, 2, 4).

Energy homeostasis is controlled through endogenous circadian rhythms that are regulated by light information, entraining an individual's behavior and physiology to the external night-day cycle (2). It is believed that changes in the light-dark exposure pattern or "inappropriate" light exposure can affect the circadian rhythm in such a way that the internal rhythms are desynchronized from both the external environment and internally with each other, which may impair sleeping behaviors and compromise metabolic processes (5–7). There is growing evidence from animal studies that disruption of circadian rhythms may lead to metabolic alterations and aspects of the metabolic syndrome, including obesity (2, 8–10), and molecular studies have shown that metabolism is directly regulated by circadian genes (11–14). In humans, night-shift workers, whose usual patterns of sleeping and eating and light-dark phases are disturbed, are more likely to be obese than day-shift workers (12, 15, 16); epidemiologic studies have shown a negative association between sleep duration and both body mass index (BMI; weight (kg)/

height $(m)^2$) and diabetes (17); and small experimental studies have shown that circadian misalignment through disruptions of sleeping and feeding patterns has adverse metabolic and cardiovascular consequences (4, 18, 19).

An increase in exposure to artificial light at night (LAN) has coincided with the increase in obesity and metabolic diseases over the last century, but whether this is coincidence or there is a causal connection has not been well investigated in humans. A recent cross-sectional study of 500 people in Japan (20) found that elderly people sleeping in lighter rooms had higher body weight, waist circumference, and BMI; in that study, light exposure and obesity outcome variables were all objectively measured, although the BMI of participants was generally low (an average of 22.8). Thus, disruption of sleep and circadian rhythms might be one mechanism contributing to the worldwide rise in obesity and metabolic syndrome (4). We therefore examined the association between LAN exposure and obesity in data from over 100,000 women in a large United Kingdom cohort study.

METHODS

Participants

The subjects were participants in the Breakthrough Generations Study, a cohort study of over 113,000 women aged 16 years or older who were living in the United Kingdom and were recruited during 2003–2012. The cohort has been described in detail elsewhere (21). Initial recruits were registered supporters of the Breakthrough Breast Cancer charity (3.8%) or women who referred themselves to the study (22.9%). Participants were able to nominate their friends and family to join the study, and the majority of participants were recruited using this method. Ethics approval for the study was obtained from the South Thames Multicentre Research Ethics Committee. Participants gave informed consent.

Variables

The participants completed a detailed baseline postal questionnaire that included a comprehensive assessment of breast cancer risk factors, including weight, height, and waist and hip circumferences, and whether these factors were measured on the day of the questionnaire, had been measured recently, or were estimated. BMI, waist:hip ratio (WHR), and waist:height ratio (WHtR) were calculated from these measurements. Given that BMI cannot distinguish between persons with high muscle mass and persons with excess adipose tissue, we also examined WHR, WHtR, and waist circumference; these measures are considered better markers of abdominal obesity, which is thought to be a key risk factor for disease (22). Four BMI groups were defined (23): underweight (<18.5), normal-weight (18.5–<25), overweight (25–<30), and obese (≥30). Four WHR groups were defined (23): underweight (<0.67), normal-weight (0.67–<0.80), overweight (0.80–<0.85), and obese (≥0.85). Two WHtR groups were defined, depending on age (24): low (<0.5 if aged <40 years, <0.55 if aged <50 years, and <0.6 if aged ≥50 years) and high (≥0.5 if aged <40 years, ≥0.55 if aged <50 years, and ≥0.6 if aged ≥50 years). Waist circumference was dichotomized (23) as low (<0.88 m; <35 inches) or high (≥0.88 m; ≥35 inches).

Exposure to LAN was assessed through participants' answers to a categorical-response question about the lightness of the room they slept in; the response categories were "light enough to read"; "light enough to see across the room, but not read"; "light enough to see your hand in front of you, but not to see across the room"; and "too dark to see your hand, or you wear a mask." The 2 lightest categories were combined because of small numbers in the lightest group (<1%). The questionnaire also asked participants to specify what times they usually went to sleep and woke up on weekdays. Answers were used to derive both the average number of hours of sleep per night and a dichotomous "nonpeak sleep" variable, where "nonpeak sleep" was defined as going to sleep at or after 2:00 AM or rising for the day at or before 1:00 AM (25) and "usual sleep" was defined as all other sleeping patterns.

Information on socioeconomic status was obtained by deriving the participant's ACORN (A Classification of Residential Neighborhoods) score, an indicator of socioeconomic status based on residential postcodes (http://acorn.caci.co.uk). Lifestyle factors entered into the multivariate models included alcohol consumption (units/week; 1 unit = 8 g), current smoking, average number of hours of sleep per night, strenuous physical activity (hours/week), recent participation in night-shift work, and having a child under 5 years of age.

Statistical analyses

Participants were eligible for these analyses if they reported anthropometric details and information about LAN exposure or sleeping patterns in the recruitment questionnaire. Multinomial logistic regression was used to examine the relationship between obesity measures and both LAN and sleeping patterns separately, after adjustment for age and the covariates described. All reported P values were 2-sided. All statistical analyses were performed in Stata, version 10.1 (StataCorp LP, College Station, Texas) (26).

RESULTS

Descriptive characteristics are shown in Table 1. Participants were between 16 and 103 years of age at recruitment (mean = 47.2 years), and the vast majority were Caucasian (98.8%). The mean BMI, WHR, WHtR, and waist circumference were 25.3, 0.81, 0.49, and 0.81 m (32 inches), respectively.

The odds of women's being overweight as compared with normal-weight were progressively lower ($P < 0.001$) among those who slept in darker rooms, measured using both BMI and WHR (Table 2); slight attenuation was seen after adjustment for covariates that may might mediate between LAN and obesity. This association was stronger for being obese than for being overweight. Trends were not clear for the odds of being underweight compared with normal-weight. Table 3 shows that the odds of a high WHtR or high waist circumference were lower among women who slept in darker

Table 1. Baseline Characteristics of 113,343 Women in the Breakthrough Generations Study, United Kingdom, 2003–2012

Variable	Mean (SD)	No.	%
Age, years	47.2 (13.6)		
Socioeconomic status (ACORN score)[a]			
A (highest)		51,914	45.8
B		12,731	11.2
C		32,079	28.3
D		8,939	7.9
E (lowest)		6,468	5.7
Unclassified[b]		126	0.1
Outside of ACORN coverage area[c]		1,086	1.0
Body mass index[d]			
Underweight (<18.5)		1,413	1.3
Normal-weight (18.5–<25)		59,326	52.3
Overweight (25–<30)		32,790	28.9
Obese (≥30)		15,497	13.7
Missing data		4,317	3.8
Waist:hip ratio			
Underweight (<0.68)		1,123	1.0
Normal-weight (0.68–<0.79)		46,949	41.4
Overweight (0.79–<0.85)		30,318	26.8
Obese (≥0.85)		28,943	25.5
Missing data		6,010	5.3
Waist:height ratio[e]			
Low for age		18,476	16.3
High for age		88,516	78.1
Missing data		6,351	5.6
Waist circumference			
Low (<0.88 m; <35 inches)		21,794	19.2
High (≥0.88 m; ≥35 inches)		86,272	76.1
Missing data		5,277	4.7
Exposure to light at night			
Lightest level		33,571	29.6
Middle level		54,803	48.4
Darkest level		23,611	20.8
Missing data		1,358	1.2
Sleeping pattern[f]			
Usual		111,986	98.8
Nonpeak		808	0.7
Missing data		549	0.5
Night-shift work in previous 10 years		18,491	16.3
Child under 5 years of age		11,856	10.5
Strenuous physical activity, hours/week	2.4 (4.1)		
Alcohol consumption, units/week (1 unit = 8 g)	12.9 (12.9)		
Current cigarette smoker		8,265	7.3
Sleep duration, hours/night	7.5 (1.0)		

Abbreviations: ACORN, A Classification of Residential Neighborhoods; SD, standard deviation.

[a] Based on residential postcode, using the ACORN algorithm (http://acorn.caci.co.uk).

[b] Primarily communal residences, such as student halls, and newly built (post-2001 United Kingdom Census) properties.

[c] Resident of the Isle of Man or the Channel Islands, for which ACORN coding is not applicable.

[d] Weight (kg)/height (m)^2.

[e] For waist:height ratio, categories were age-dependent: "low" was defined as <0.5 if aged <40 years, <0.55 if aged <50 years, and <0.6 if aged ≥50 years; "high" was defined as ≥0.5 if aged <40 years, ≥0.55 if aged <50 years, and ≥0.6 if aged ≥50 years.

[f] Nonpeak sleep was defined, as in the study by Davis et al. (25), as going to sleep at or after 2:00 AM or rising for the day at or before 1:00 AM; usual sleep was defined as all other sleeping patterns.

rooms; there was some attenuation after adjustment for potentially mediating covariates ($P < 0.001$).

Analyses were repeated after excluding women who stated that their reported measurements were estimated, women who reported certain illnesses at study entry (history of cancer (except nonmelanoma skin cancer), diabetes, thyroid disease, or hip fracture), and women who had had a child in the 5 years before completing the questionnaire—that is, factors which might affect the lightness of the bedroom or the risk of being overweight. Further adjustment for factors that might mediate between LAN and obesity, such as various dietary items, did not alter our results. Although the prevalence of nonpeak sleep was low, this was also examined in relation to measures of obesity, with similar results: Women who slept at nonpeak hours, versus usual hours, had a raised risk of being overweight (the fully adjusted odds ratio was 1.31 (95% confidence interval (CI): 1.10, 1.57) for BMI and 1.17 (95% CI: 0.97, 1.42) for WHR) and an even greater risk of being obese (the odds ratio was 1.96 (95% CI: 1.62, 2.37) for BMI and 1.65 (95% CI: 1.39, 1.97) for WHR) as compared with normal-weight.

DISCUSSION

In this analysis of over 113,000 United Kingdom women, BMI, WHR, WHtR, and waist circumference increased with increasing lightness of the room slept in at night. These associations were still present after adjustment for age, socioeconomic status, alcohol consumption, strenuous physical activity, night-shift work, having a young child, sleep duration, and current smoking. Our results are consistent with those of the only previous study examining LAN exposure and human obesity of which we are aware (20), in which (among 500 participants) higher body weight, waist circumference, and BMI were seen in persons who slept in lighter rooms; with animal experiments showing that increased light exposure can affect the regulation of metabolism and

Table 2. Odds Ratio for Being Underweight, Overweight, or Obese According to Degree of Light-at-Night Exposure Among Women From the Breakthrough Generations Study, United Kingdom, 2003–2012[a]

	Total No. of Women	Weight Category (vs. Normal-Weight) and Level of Light at Night (vs. Lightest Level)											
		Underweight				Overweight				Obese			
		Middle Level		Darkest Level		Middle Level		Darkest Level		Middle Level		Darkest Level	
		OR	95% CI	OR	95% CI	OR	95% CI	OR	95% CI	OR	95% CI	OR	95% CI
Age-adjusted OR													
Body mass index[b,c]	108,285	0.99	0.88, 1.12	1.06	0.91, 1.23	0.95[d]	0.92, 0.98	0.86[e]	0.82, 0.89	0.86[e]	0.82, 0.89	0.75[e]	0.72, 0.79
Waist:hip ratio[f]	106,624	0.86	0.75, 0.99	0.89	0.75, 1.05	0.95[e]	0.92, 0.99	0.91[e]	0.87, 0.95	0.89[e]	0.86, 0.92	0.84[e]	0.81, 0.88
Multivariate-adjusted OR[g]													
Body mass index	103,839	0.98	0.86, 1.11	1.05	0.90, 1.23	0.97	0.94, 1.00	0.90[e]	0.87, 0.94	0.90[e]	0.87, 0.94	0.83	0.79, 0.88
Waist:hip ratio	102,276	0.86	0.75, 0.99	0.90	0.76, 1.07	0.97	0.94, 1.00	0.93[e]	0.89, 0.97	0.92[e]	0.89, 0.96	0.90[e]	0.86, 0.94

Abbreviations: CI, confidence interval; OR, odds ratio.
[a] *P* values (2-tailed tests) were estimated using the Wald test, under the null hypothesis that OR = 1.
[b] Weight (kg)/height $(m)^2$.
[c] Body mass index groups: underweight, <18.5; normal-weight, 18.5–<25; overweight, 25–<30; obese, ≥30.
[d] $P < 0.01$.
[e] $P < 0.001$.
[f] Waist:hip ratio groups: underweight, <0.67; normal-weight, 0.67–<0.80; overweight, 0.80–<0.85; obese, ≥0.85.
[g] Multivariate results were adjusted for age, having a child under age 5 years, socioeconomic status, night-shift work in the previous 10 years, strenuous physical activity, alcohol consumption, sleep duration, and current smoking status.

cause gains in fat (27) and body mass (2), even when calorie intake and daily activity levels are kept constant; and with genetic studies showing that circadian clock genes are involved in energy regulation as well as sleep-wake regulation (4). While trends in underweight women were inconsistent, these women might be underweight for specific pathological reasons such as illness or anorexia, which may mask a potential association with LAN.

The light-dark cycle is the main synchronizer of the circadian clock (5, 6), with melatonin acting as the transducer. Melatonin production is inhibited by exposure to light (6), and stronger inhibition is seen with increased light intensity and length of exposure (5); even normal room light as compared with dim light has been shown to cause suppression of melatonin onset and reduce the duration of melatonin secretion in the vast majority of individuals (28). Melatonin rhythms play an important role in metabolic function and may influence circadian-clock gene expression in the peripheral tissues involved in metabolism (10). Thus, exposure to room light may inhibit the production of melatonin and therefore alter

Table 3. Odds Ratio for Having a High (vs. Low) Waist:Height Ratio or Waist Circumference According to Degree of Light-at-Night Exposure (vs. Lightest Level) Among Women From the Breakthrough Generations Study, United Kingdom, 2003–2012[a]

	Total No. of Women	Level of Light at Night			
		Middle Level		Darkest Level	
		OR	95% CI	OR	95% CI
Age-adjusted OR					
Waist:height ratio[b]	106,290	0.87[c]	0.84, 0.90	0.76[c]	0.74, 0.81
Waist circumference[d]	107,351	0.90[c]	0.87, 0.93	0.84[c]	0.81, 0.88
Multivariate-adjusted OR[e]					
Waist:height ratio	101,978	0.91[c]	0.88, 0.95	0.86[c]	0.82, 0.90
Waist circumference	102,960	0.94[c]	0.91, 0.97	0.91[c]	0.87, 0.96

Abbreviations: CI, confidence interval; OR, odds ratio.
[a] *P* values (2-tailed tests) were estimated using the Wald test, under the null hypothesis that OR = 1.
[b] For waist:height ratio, categories were age-dependent: "low" was defined as <0.5 if aged <40 years, <0.55 if aged <50 years, and <0.6 if aged ≥50 years; "high" was defined as ≥0.5 if aged <40 years, ≥0.55 if aged <50 years, and ≥0.6 if aged ≥50 years.
[c] $P < 0.001$.
[d] Low waist circumference, <0.88 m (<35 inches); high waist circumference, ≥0.88 m (≥35 inches).
[e] Multivariate results were adjusted for age, having a child under age 5 years, socioeconomic status, night-shift work in the previous 10 years, strenuous physical activity, alcohol consumption, sleep duration, and current smoking status.

physiological processes that are regulated by melatonin signaling.

Another mechanism by which disruption of the circadian rhythm might cause obesity is sleep duration. Previous experimental research in both animals and humans has shown associations between sleep loss and obesity, potentially through changes in carbohydrate metabolism and endocrine function (4). One small experimental study in humans showed that sleep duration was correlated with the proportion of weight loss due to fat loss, with short sleepers losing less fat than longer sleepers despite a similar overall weight loss (29). Epidemiologic studies have also shown associations between short sleep duration and obesity (30). However, differences in sleep duration did not explain the increased obesity seen in women with higher LAN exposure in our cohort.

Food is an important external synchronizer for internal circadian rhythms. Hence, unusual feeding times might also contribute to chronodisruption and obesity (31). Studies in animals have shown that being active and feeding during the usual rest phase leads to alterations in metabolism and weight gain, even with the same caloric intake (2). Studies in humans have shown that night-shift work is associated with detrimental changes in weight, carbohydrate and lipid metabolism, insulin resistance, and heart disease (32) and that phase-delayed eating patterns, such as not eating breakfast or night-eating syndrome, are associated with increased BMI and altered metabolism (33).

While BMI and WHR are the most commonly used measures of overweight and obesity in study populations, both have their limitations: BMI does not distinguish between persons with excess adipose tissue and those with high muscle mass (22), and WHR may not accurately reflect changes in body size if hip and waist circumferences change proportionately (22). Therefore, we also examined WHtR and waist circumference, which are considered better markers of abdominal obesity (22), with similar findings.

Limitations of our study include the self-reported measurements of obesity variables and the self-reported information on exposure to LAN. We have not yet validated the variable used to estimate LAN exposure, so we cannot estimate the light intensity in each category. Comparisons between self-reported measurements of height and waist circumference and those taken by trained technicians following a standardized protocol for a sample of Breakthrough Generations Study women have shown a reasonable degree of accuracy (34). Furthermore, since the potential link between obesity and LAN is not well known, any misclassification is likely to have been nondifferential. Excluding subjects who stated that their weight and height data were estimates rather than measurements did not affect the results. It was not possible to assess calorie intake or timing of meals—factors that might mediate between LAN and obesity—in the present study (2). However, adjustment for alcohol intake, physical activity level, and various dietary items did not alter our results. It is conceivable that our results might have been due to reverse causation, though exactly how is not obvious.

In conclusion, we found evidence of a significant association between LAN exposure and obesity in humans that was not explained by potential confounders we could measure. While the possibility of residual confounding cannot be excluded, the pattern is intriguing and warrants further investigation, particularly because there could be much potential for preventive measures.

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