Effects of artificial light at night on human health: A literature review of observational and experimental studies applied to exposure assessment

YongMin Cho, Seung-Hun Ryu, Byeo Ri Lee, Kyung Hee Kim, Eunil Lee & Jaewook Choi

Published online: 16 Sep 2015.

Submit your article to this journal ⤤

View related articles ⤤

View Crossmark data ⤤

Taylor & Francis
Taylor & Francis Group

REVIEW ARTICLE

Effects of artificial light at night on human health: A literature review of observational and experimental studies applied to exposure assessment

YongMin Cho[1], Seung-Hun Ryu[1], Byeo Ri Lee[1], Kyung Hee Kim[1], Eunil Lee[2], and Jaewook Choi[1,2]

[1]Institute for Occupational & Environmental Health, Korea University, Seoul, Republic of Korea and [2]Department of Preventive Medicine, College of Medicine, Korea University, Seoul, Republic of Korea

It has frequently been reported that exposure to artificial light at night (ALAN) may cause negative health effects, such as breast cancer, circadian phase disruption and sleep disorders. Here, we reviewed the literature assessing the effects of human exposure to ALAN in order to list the health effects of various aspects of ALAN. Several electronic databases were searched for articles, published through August 2014, related to assessing the effects of exposure to ALAN on human health; these also included the details of experiments on such exposure. A total of 85 articles were included in the review. Several observational studies showed that outdoor ALAN levels are a risk factor for breast cancer and reported that indoor light intensity and individual lighting habits were relevant to this risk. Exposure to artificial bright light during the nighttime suppresses melatonin secretion, increases sleep onset latency (SOL) and increases alertness. Circadian misalignment caused by chronic ALAN exposure may have negative effects on the psychological, cardiovascular and/or metabolic functions. ALAN also causes circadian phase disruption, which increases with longer duration of exposure and with exposure later in the evening. It has also been reported that shorter wavelengths of light preferentially disturb melatonin secretion and cause circadian phase shifts, even if the light is not bright. This literature review may be helpful to understand the health effects of ALAN exposure and suggests that it is necessary to consider various characteristics of artificial light, beyond mere intensity.

Keywords: Artificial light at night, breast cancer, circadian rhythm, light exposure, light pollution

INTRODUCTION

Light is a necessity for a comfortable life, productivity and safety of human beings. More than ever, modern humans rely on artificial light for a substantial part of the day. While artificial light increases convenience, excessive exposure to artificial light may have negative impacts on ecosystems and on human health (Gaston et al., 2015; Haim & Zubidat, 2015). Moreover, because of this increased use of artificial light, humans spend less time in the dark at night.

The most common health effects of artificial light at night (ALAN) are disruption of the biological clock and suppression of the nocturnal production of melatonin (Reiter et al., 2007). This ALAN-induced circadian disruption and suppression of melatonin secretion are associated with an increased cancer risk (Blask, 2009; Davis & Mirick, 2006; Kantermann & Roenneberg, 2009; Stevens et al., 2007, 2014). More specifically, several

ecological and observational studies have shown that greater levels of exposure to ALAN may increase the risk of breast (Bauer et al., 2013; Chepesiuk, 2009; Kloog et al., 2008, 2010; Yang et al., 2014) and prostate cancers (Kloog et al., 2009) in the population.

Aside from cancer, sleep disturbance due to ALAN exposure may also have an impact on aging and metabolic processes (Hood et al., 2004; Stevens et al., 2007), as well as on heart disease, diabetes, mood disorders and obesity, which have become pandemic (Gangwisch, 2014; Stevens, 2009). Therefore, ALAN exposure increases public health concerns in modern societies (Dickerman & Liu, 2012).

However, which characteristics of ALAN affect human health requires further investigation. Given that ALAN is a single potential environmental risk factor (Dickerman & Liu, 2012), it does not affect the human body in the form of direct toxicity or physical energy, as other environmental risk factors, i.e. chemical

toxicants or radiation, do. Consequently, unlike other risk factors, it is difficult to explain the dose–response relationship of ALAN *per se*.

To understand how ALAN affects the human body and to prevent its effects on public health, it may be necessary to establish which aspects of ALAN exposure are associated with these health effects. Therefore, we conducted a literature review of the observational and experimental studies assessing the effects of ALAN exposure. In such studies, the estimated individual (or grouped) ALAN exposure level, controlled bright light exposure or similar control of other characteristics of light exposure, such as wavelength and exposure duration, were viewed as exposure factors. The reported impact of ALAN on humans is listed according to the characteristics of ALAN exposure.

METHODS

Articles published through August 2014 were collected from several electronic databases (PubMed, ScienceDirect and ScholarOne). Only peer-reviewed articles were collected for this review and conference reports and proceedings were excluded. The articles collected were those that assessed the effects of exposure to ALAN on human health. The terms used in the search (in full text) were as follows: (light at night OR dim light OR artificial light) AND (sleep) AND (exposure) AND (health OR melatonin OR circadian OR breast cancer), (light at night) AND (light pollution OR light exposure OR health) AND (artificial light OR light at night OR health) AND (exposure assessment OR light pollution). Further relevant publications were obtained by scanning the reference lists of the collected articles.

The criteria for inclusion in the literature review were original research articles that specified the methods used for assessment of exposure of ALAN or LAN (light at night) exposure assessment in human subjects. Exposure assessment studies refer to studies that identified the relationship between ALAN exposure and health outcomes that also include the actual measurements of ALAN levels, the lighting habits of individuals by means of questionnaires and experimental trials in which subjects were exposed to lighting in a controlled way. Ecological studies were included in the analysis on ALAN level and the incidence of disease.

Studies that did not investigate the impact of artificial light were excluded. For example, studies on health effects from polar night at high latitudes, studies mainly focused on daytime exposure (or ultraviolet exposure from sun light), rather than on nighttime exposure to light, studies assessing the treatment effects of daytime or morning light exposure (particularly for depression and dementia), studies examining non-day shift workers that did not use ALAN as an evaluation factor and studies measuring light pollution that only evaluated light emission, but not the impact on humans, were all excluded. Review papers and brief letters that were not

original articles were also excluded from the analysis, as were animal, *in vivo/vitro*, and cell studies.

The data in each article were individually reviewed by two researchers and recorded in a standardized form. This form included the following categories: study design, exposure conditions and factors, reason for exclusion (when excluded), study subjects, health outcome, methods applied to assess outcome, units for exposure assessment, exposure factor considered and main results. The advantages, particulars and limits of the research were also recorded. When there were differences between the information recorded by each reviewer, the paper was reviewed again.

RESULTS

Among the 412 articles collected, 261 papers were excluded from the analysis after reviewing the abstracts (one of which was duplicated). After the full text review, 66 additional papers were excluded. Ultimately, 85 papers were included in the literature review (Figure 1).

The ALAN exposure conditions applied in each study were divided into light intensity, exposure characteristics and light characteristics. These are the characteristics considered as ALAN exposure factors by the researchers. The health effects that were demonstrated in response to each exposure factor were described.

Light intensity
Outdoor ALAN level
Among the studies that applied outdoor ALAN level as a surrogate marker, individual or group residential areas were found to be a key factor. Data from the United States Department of Defense's Defense Meteorological Satellite Program (DMSP) were generally used to determine the outdoor ALAN level. Kloog and colleagues used the DMSP data in their ecological studies to show that the ALAN level increased the risk of breast cancer in women and of prostate cancer in men; these results were independent of other cancers, including lung cancer (Kloog et al., 2008, 2009, 2010). In a case-referent study that compared the ALAN exposure level of breast cancer cases and lung cancer referents among registered cancer patients in Georgia, USA, the DMSP data were also used to show that breast cancer incidence was associated with increased ALAN exposure (Bauer et al., 2013). Similarly, DMSP data were used for a cohort study targeting female teachers in California, USA, which showed an association between outdoor ALAN levels and breast cancer (Hurley et al., 2014). When examining other health effects of outdoor ALAN exposure, it was found that adolescents living in city areas with a high ALAN level had a stronger evening-type inclination than adolescents living in relatively dark rural areas (Vollmer et al., 2012). However, Hurley et al. reported no relevant correlations between the outdoor ALAN level and urinary 6-sulfatoxymelatonin concentration, a proxy for circulating melatonin levels, in a

FIGURE 1. PRISMA diagram of the screening process (Adapted from Moher et al., 2009).
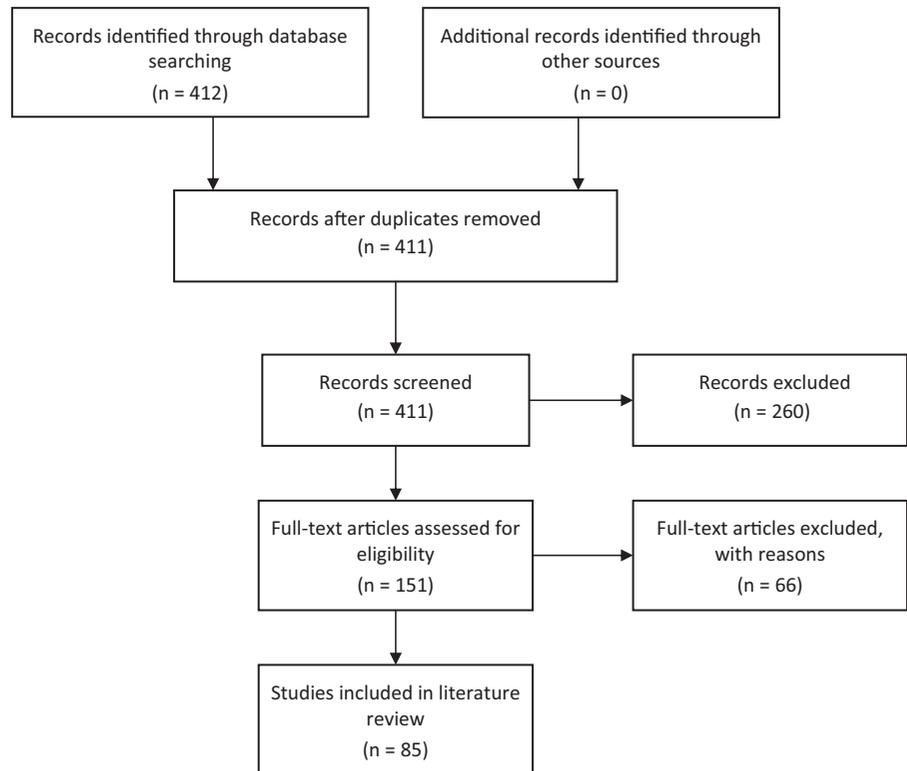
cross-sectional study based on DMSP data (Hurley et al., 2013).

Individual lighting habits

Davis et al. evaluated individual ALAN exposure levels in a survey on sleep habits and bedroom lighting characteristics (Davis et al., 2001). This study reported that lighting habits while sleeping did not increase the risk of breast cancer, but night shift work did so. In further studies, these and similar survey items were used as factors to evaluate the individual ALAN level while sleeping. These did not involve measurements of actual light intensity, but rather was an attempt to classify the estimated ALAN level exposure in bed.

Kloog et al. divided the nighttime bedroom light level into a four-point scale, ranging from ''completely dark'' to ''very strong light – all lights switched on'', and reported that the odds ratio (OR) of breast cancer incidence was significantly predicted by light intensity (Kloog et al., 2011). In a population-based case-control study by O'Leary et al. in the USA, it was reported that the groups that turned on the light in bed more frequently had an increased risk of breast cancer (O'Leary et al., 2006). However, research by Li et al. did not find any significant correlation between exposure to indoor lighting factors, such as bedroom lighting, or television viewing habits, and the risk of breast cancer (Li et al., 2010).

A study on interactions between occupational exposure to low-frequency magnetic fields and ALAN reported that melatonin secretion was significantly decreased after exposure to both magnetic fields and ALAN (Juutilainen & Kumlin, 2006). In addition, women who slept later were reported to show a trend toward having high serum estradiol and testosterone levels and a low urinary 6-sulfatoxymelatonin level (Nagata et al., 2008; Wada et al., 2012). However, Wada et al. failed to find a significant difference in the concentration of melatonin among preschool children in Japan exposed to different levels of ambient bedroom light (Wada et al., 2013a). Another study has reported that a group with lower bedroom brightness showed reduced obesity rates (McFadden et al., 2014), while another study showed no correlation with myopia in children (Czepita et al., 2012).

Indoor illumination level

In some observational studies, individual light exposure or indoor illumination intensity during subjects' daily lives were directly measured, using devices, such as a photometer, ActiWatch, StowAway light intensity data logger or a HOBO pendant.

Melatonin levels were found to be significantly lower in nurses who work night shifts than in those who work day shifts, and the former were also exposed to significantly more intense light levels (lumen/m^2) during sleep (Grundy et al., 2009). In addition, rotating shift workers with erratic levels of light exposure also showed abnormal melatonin levels (Borugian et al., 2005). Furthermore, when subjects whose chronotypes were the morning- or evening-type were exposed to light at different times of day, no difference was identified when

light exposure was adjusted for their circadian phase (Goulet et al., 2007). Similarly, the total amount of light exposure did not differ between night nurses whose melatonin release timing had adapted to night shift work by circadian phase advance, circadian phase delay or by no change in circadian phase; however, the 24-h profile of light exposure was different among groups (Dumont et al., 2001).

In a study conducted by Obayashi et al., a significantly higher OR for subjective insomnia was identified within the group exposed to more intense ALAN (Obayashi et al., 2014c). In another study, evening-type subjects with higher light exposure levels had poor sleep quality and fatigue (Martin et al., 2012). It was also reported that adolescents with delayed sleep phase disorder (DSPD) were exposed to significantly brighter ALAN than the control group (Auger et al., 2011). In addition, an increase in evening and nighttime light exposure significantly raised sleep onset latency (SOL) (Obayashi et al., 2014b). According to a study by Wallace-Guy et al., light exposure over 4 h prior to bedtime was not significantly related to SOL, sleep amount or depressed mood; while the total amount of illumination over 24 h period was correlated with a shorter SOL, reduced waking during sleep and a less depressed mood (Wallace-Guy et al., 2002). In a study on elderly depression, the depressed group had significantly higher ALAN exposure than the non-depressed group (Obayashi et al., 2013a).

In studies which measured ALAN exposure during the nighttime by installing a 1-min interval light meter at the bedside, it was reported that ALAN exposure was associated with a higher OR for obesity (BMI) and dyslipidemia (Obayashi et al., 2013b), and significantly increased nighttime blood pressure (Obayashi et al., 2014a). In addition, circadian changes were weaker in a group with a lower day−night light contrast (Martinez-Nicolas et al., 2014).

Bright light exposure at night
In studies of nocturnal sleep or sleep deprivation, differences in the physiological reactions between a bright light (BL) exposure group and a dim light (DL) exposure group were frequently assessed using within- or between-subject designs.

In one study, BL exposure at 2500−2800 Lux suppressed melatonin secretion relative to DL exposure at <100−120 Lux (Bunnell et al., 1992; Yokoi et al., 2006). Compared to exposure to DL at <10 Lux, a BL group had lower melatonin concentrations when exposed to 100 Lux and showed greatly lowered levels after exposure to 5000 Lux (Rüger et al., 2005). Exposure to BL during nighttime can reduce nocturnal melatonin concentrations in adolescents (Harada, 2004), and melatonin concentration declines when the eyes are exposed to BL (Hätönen et al., 1999; Rüger et al., 2003). In one study, melatonin secretion was suppressed when exposed to white BL (3000 Lux) relative to red DL (<15 Lux), while

no difference in cortisol secretion was observed (Lavoie et al., 2003). In addition, BL-induced melatonin suppression was much higher in subjects diagnosed with premenstrual dysphoric disorder (PMDD) (Parry et al., 2010).

In a group exposed to BL at approximately 3000 Lux, a significantly higher DL melatonin onset (DLMO) was observed compared to a group exposed to DL at 1.9 Lux (Burke et al., 2013). Likewise, while a high level of night light exposure induced a DLMO delay (Benloucif et al., 2006; Figueiro & Rea, 2012), a phase response curve (PRC) was created when exposed to bright white light at 8000 Lux for an hour, this was not observed when exposed to DL at <3 Lux (St Hilaire et al., 2012).

Compared to DL (<3 Lux), exposure to moderate light (<200 Lux) before bedtime (ca. 24:00) suppressed melatonin, resulting in a later melatonin onset (Gooley et al., 2011). A significant circadian phase shift was found when exposed to a very bright light at 9500 Lux (Shanahan et al., 1999). Iris color did not affect DLMO phase delay significantly (Canton et al., 2009).

Zeitzer et al. (2005) reported that melatonin phase shift and melatonin suppression increased with Lux, showing a nonlinear increase that rose rapidly at 100 Lux. However, according to research conducted by Foret et al. (1996), nighttime BL (1000 Lux) exposure suppressed levels of the melatonin metabolite aMT6s, while exposure to 100 Lux did not. On the other hand, it was also reported that an increase in the intensity of illumination (2000–8000 Lux) did not change DLMO (Dewan et al., 2011) and that extraocular light exposure had no impact on phase delay or melatonin secretion (Lushington et al., 2002).

Furthermore, when individuals were exposed to 40 Lux ALAN with the source at 1 m away from the eyes during sleep, they slept less deeply, demonstrated periodic arousal and had altered brain activity (Cho et al., 2013). When exposed to BL, sleep latency was high (Bunnell et al., 1992; Komada et al., 2000; Lavoie et al., 2003; Tzischinsky & Lavie, 1997), and exposure to BL during nighttime delayed sleep initiation and reduced overall sleep quality (Kubota et al., 1998; Tzischinsky & Lavie, 1997). Exposure to BL during the night inhibits alertness and task performance (Chang et al., 2013; Daurat et al., 2000), maintains high skin and rectal temperature (Bunnell et al., 1992; Kubota et al., 1998; Lavoie et al., 2003; Rüger et al., 2006; Yokoi et al., 2003, 2006) and increases the heart rate and systolic blood pressure (Kohsaka et al., 2001; Rüger et al., 2006; Yokoi et al., 2006). In an experiment by Rüger et al., sleepiness on the Karolinska Sleepiness Scale was not reduced by nighttime exposure to 100 Lux, but was significantly reduced by exposure to 5000 Lux (Rüger et al., 2003, 2005) and also significantly dropped after exposure to BL at >2500 Lux relative to DL (<150 Lux) (Yokoi et al., 2003).

Additionally, there were no differences in the amount of breath hydrogen induced by exposure to BL relative

to DL (Hirota et al., 2010). Exposure to BL during the night decreased leg discomfort in patients with restless legs syndrome (Whittom et al., 2010).

Exposure characteristics
Exposure duration/time
Chang et al. reported that light exposure during sleep could suppress melatonin acutely and induce subjective sleepiness in a manner dependent on the duration of the light exposure (Chang et al., 2012). In another experiment, conducted by Dewan et al., an increase in the duration, but not the intensity of light exposure, altered the circadian melatonin rhythm (Dewan et al., 2011). In addition, exposure to BL for 4 h, but not 2 h, increased sleep latency but improved task performance (Thessing et al., 1994). All night BL exposure induced greater increases in alertness and performance than observed after short exposure (Daurat et al., 2000), and the change in the circadian phase shift becomes clearer as the exposure continued (Deacon & Arendt, 1994). In addition, the effects of light exposure on the circadian melatonin rhythm and alertness are affected by the history of prior light exposure (Chang et al., 2011, 2013).

Carrier and Dumont exposed subjects to BL at different times of day, and found that evening exposure induced a greater shift in the circadian temperature rhythm than exposure in the morning or afternoon (Carrier & Dumont, 1995). Comparison between evening and early morning BL exposure showed that evening BL exposure affected the circadian phases (rectal body temperature, melatonin, phase delay) (Foret et al., 1998; Gordijn et al., 1999).

Light:dark cycle
Both transient sleep displacement and habitual changes in sleep time bring about delays in DLMO (Gordijn et al., 1999; Wright et al., 2005). In addition, short nights associated with evening light exposure can reduce circadian phase advances (Burgess, 2013). Both clock gene expression and the circadian melatonin rhythm were also altered by a 40-h period of continuous sleep deprivation and light exposure (Cajochen et al., 2003; Kavcic et al., 2011).

Light characteristics
Several studies have reported the biological impacts of light characteristics beyond merely light intensity. Subjects exposed to 460-nm ALAN experienced decreased subjective drowsiness and increased alertness compared to those exposed to 550-nm ALAN (Lockley et al., 2006; Rahman et al., 2014). Exclusion of shorter wavelength light (<480 nm) prevented both the suppression of melatonin secretion and alterations in circadian temperature rhythm, increased cortisol secretion, disrupted peripheral clock gene expression (Rahman et al., 2011; van de Werken et al., 2013) and had reduced effects on circadian temperature fluctuation. Blue light exposure decreased both melatonin

concentration and sleepiness while raising alertness (Phipps-Nelson et al., 2009; Santhi et al., 2012; Wahnschaffe et al., 2013). Even at a low intensity, blue-enriched light can influence EEG (electroencephalographic) activity during sleep (Chellappa et al., 2013). In contrast, another study found that nighttime performance and sleepiness ratings were not strongly affected by blue-enriched light, but melatonin levels were (Figueiro et al., 2009).

Light with a higher color temperature (6500 K) more strongly suppressed circadian temperature and melatonin rhythms than did a cooler (3000 K) light (Morita & Tokura, 1996). Similarly, another study found that melatonin is suppressed by exposure to artificial light with a high color temperature, but not by light with a low color temperature (Wada et al., 2013b).

DISCUSSION

Artificial light exposure at night causes a suppression of melatonin, deterioration in sleep quality and disturbance in biorhythms. Such effects increase with the brightness of the light and the length of the exposure period. Even light that is not particularly bright can have a stronger influence if the light is blue, with a shorter wavelength, or if the exposure occurs in the evening before going to bed. Habitual lighting of the bedroom may also have an impact on circadian rhythms and increase cancer risk, and bright outdoor settings can act as a risk factor for cancer.

With regard to exposure to light, the intensity, duration and biological time of exposure all have critical effects on the circadian rhythm (Küller, 2002; Reiter et al., 2007; Wright et al., 2005). In addition, suppression of melatonin caused by light exposure is dependent on the intensity and wavelength (Blask, 2009; Skene et al., 1999). Therefore, the health effects of ALAN are related to the exposure conditions and characteristics of the light, and not only to the amount of light.

Exposure conditions of light that may cause negative health effects
Most environmental pollutants cause negative health effects when humans are exposed to an "amount" in excess of a threshold. In the case of light, the "amount" may mean not only the intensity, but also the duration and cycle of exposure. Excessive noise causes a hearing loss, but noise is defined as unwanted sound, rather than excessive (absolutely too loud) sound, and brings about many types of health effects besides hearing defects. As in the case of noise, unwanted light at night means not only excessive light in terms of brightness.

Some experimental studies reviewed here reported that brighter light induced greater health effects, i.e. melatonin concentration reduction. However, the threshold of light intensity that triggers a response in terms of human health effects is unknown. One study used a DL condition of 100 Lux and found no melatonin

TABLE 1. Observational studies of exposure to artificial light at night (ALAN) and health outcomes.

Factor of LAN considered/data source of exposure	Study design	Subjects	Main confounders considered	Significant associations	Outcome assessment[b]/main statistics applied	References
Outdoor ALAN level/satellite data	Ecological	–	Race, per capita income, population, birth rate, electricity consumption, fertility rate, lung cancer[a]	Incidence of BC (ASR)	$B=0.121$ and 0.277/OLS regression	Kloog et al. (2008, 2010)
	Ecological	–	GDP, urban population, electricity consumption, region, lung cancer[a]	Incidence of prostate cancer (ASR)	$B=0.150-0.160$/OLS regression	Kloog et al. (2009)
	Case-referent	34 053 BC cases and 14 458 lung cancer referents	Race, tumor grade and stage, smoking, statistical status, etc.	Incidence of BC	OR for LAN $=1.12$ (95% CI $=1.04-1.20$)/Logistic regression	Bauer et al. (2013)
	Cohort	106 731 women	Age, race, birthplace, family history of BC, menses, pregnancy, breastfeeding, etc.	Incidence of BC	$HR=1.12$ and 1.34 (95% CI $=1.00-1.26$; $1.07-1.69$, respectively) Cox proportional hazards regression	Hurley et al. (2014)
	Cross-sectional	1507 adolescents	Time use of electronic screen media, intake of stimulants, type of school, age, puberty status, etc.	Chronotype (eveningness-type)	$B=-0.105$ (between LAN and chronotype)/regression analysis	Vollmer et al. (2012)
	Cross-sectional	303 adults	Age, parity, pregnancy, smoking, alcohol, contraceptive, hormone therapy, menopausal status, etc.	Urinary aMT6s concentration[n.s]	$B=-0.0028$ and -0.0062 ($p=0.73$ and 0.62)/regression analysis (stepwise approach)	Hurley et al. (2013)
Lighting habit/questionnaire for nighttime bedroom lighting or sleep time	Case-control	794 with BC and 885 controls	Education, ethnicity, fertility, alcohol consumption, TV on while sleeping	Incidence of BC	OR for bedroom light $=1.220$ (95% CI $=1.118-1.311$)/logistic regression	Kloog et al. (2011)
	Case-control	576 with BC and 585 controls	Menopausal status, history of oophorectomy or hysterectomy, smoking, hormone therapy	Incidence of BC	OR for lighting habit during sleep hrs $=1.65$ (95% CI $=1.02-2.69$)/logistic regression	O'Leary et al. (2006)
	Cross-sectional	60 women	Daytime occupational electromagnetic exposure, [c]age, smoking	Excretion of 6-OHMS	The lowest mean in the group of both MF and LAN/ANOVA	Juutilainen & Kumlin (2006)
	Longitudinal	206 postmenopausal women	Age, BMI, smoking and drinking habits, physical activity, medical and reproductive history, day length of the day previous to urine collection	Concentration of serum estradiol and urinary 6-sulfatoxymelatonin	The lower geometric means in women who were not asleep at or after 1:00a.m./ANOVA	Nagata et al. (2008)

	Study design	Sample	Confounders	Outcome	Results	Reference
	Longitudinal	236 women	Age, sex of offspring, parity, smoking, pre-pregnant height and weight, weeks of gestation	Maternal and umbilical serum testosterone level	Higher among those who were awake at or after 01:00 a.m./Student's t-test and correlation test	Wada et al. (2012)
	Cross-sectional	113 343 women	Alcohol consumption, smoking, hours of sleep, physical activity, shift work, childbirth history, age, socioeconomic status	BMI, waist:hip ratio, waist:height ratio, waist circumference	Significant ORs of indicators of obesity for middle or darkness level compared with the lightest level = 0.94 −0.76/logistic regression	McFadden et al. (2014)
	Case-control	813 BC patients and 793 controls	Parity, family history of BC, oral contraceptive use, hormone replacement therapy	BC prevalence[n.s]	OR for ambient light levels = 1.0–1.4 (not significant)/logistic regression	Davis et al. (2001)
	Case-control	363 BC cases and 356 controls	Age, race and ethnicity, BMI, age at first menstrual period, menopausal status, lactation, family history of BC, alcohol consumption, smoking, age at first full-term birth	BC incidence[n.s]	OR for keeping lights on while sleeping = 1.4 (95% CI = 0.7–2.7)/logistic regression	Li et al. (2010)
	Cross-sectional	438 children	Age, BMI, sex, sex steroid hormones	Melatonin levels[n.s]	No significant difference between factors of bedroom ambient light level/ANOVA	Wada et al. (2013a)
	Cross-sectional	3905 schoolchildren	Family history of myopia and eye health status	Myopia incidence[n.s] during school years	Not associated with lighting conditions until the age of two years/Chi-square test	Czepita et al. (2012)
Indoor illumination level/ light intensity data logger (real measurement in living)	Cross-sectional	61 female rotating shift nurses	Health history, medication use, smoking, alcohol and caffeine consumption, sleep duration, physical activity, parity	Melatonin concentration	Parameter estimate = −0.40 (log ng/ mL); $p = 0.002$/multiple linear regression	Grundy et al. (2009)
	Cross-sectional	22 shift workers	Medication, education, marital status, menopausal status	Melatonin concentration	$p = 0.002$ between melatonin categories and shift types/likelihood-ratio X^2 test	Borugian et al. (2005)
	Cross-sectional	857 elderly individuals	Age, gender, BMI, daytime physical activity, UME, bedtime, rising time, day length	Insomnia, Sleep quality	Final adjusted OR = 1.61 (95% CI = 1.05–2.45)/ linear regression model for trends	Obayashi et al. (2014c)
	Cross-sectional	88 student workers		Sleep quality, fatigue		Martin et al. (2012)

(continued)

TABLE 1. Continued

Factor of LAN considered/ data source of exposure	Study design	Subjects	Main confounders considered	Significant associations	Outcome assessment[b]/ main statistics applied	References
			Commuting time, living environment, number of days off		Sleep on and offset time of E-type were different from M-type/ANOVA	
	Cohort	16 adolescents with DSPD and 22 unaffected controls	Mood and depression, medication use, tobacco and caffeine	DSPD	Higher light exposure in the evening time in the DSPD group/repeated measures linear model	Auger et al. (2011)
	Longitudinal	192 elderly individuals	Alcohol consumption, BMI, smoking, income, education, sleep medication use, eGFR, daytime physical activity	Sleep onset latency	$B=0.133$ (95% CI $= 0.020–0.247$) for evening light exposure/linear regression	Obayashi et al. (2014b)
	Cross-sectional	154 women	Age, season	Depressed mood, sleep latency	$R=-0.29$ ($p<0.001$) for sleep latency and $R=-0.21$ ($p<0.01$) for depressed mood with a 24-h illumination/multiple regression	Wallace-Guy et al. (2002)
	Cross-sectional	516 elderly individuals	BMI, smoking, alcohol consumption, SES, sleep duration, habitual bedtime, eGFR, diabetes, medical history, daytime exposure, etc.	Depressive symptoms	aOR for light intensity (≥ 5 Lux) $= 1.89$ (95% CI $= 1.10–3.25$), aOR for exposure duration (≥ 30 min) $= 1.71$ (95% CI $= 1.01–2.89$)/logistic regression	Obayashi et al. (2013a)
	Cross-sectional	528 elderly individuals	Smoking, drinking, income, education, medications, habitual sleep duration and bedtime, day length, physical activities	Obesity, dyslipidemia	aOR for BMI (of LAN ≥ 3 Lux) $= 1.89$ (95% CI $= 1.18–3.04$), aOR for abdominal $= 1.62$ (95% CI $= 1.02–2.57$), aOR for dyslipidemia $= 1.72$ (95% CI $= 1.11–2.68$)/logistic regression	Obayashi et al. (2013b)

Study design	Subjects	Outcome variable	Confounders/adjusted variables	Results/method	Reference
Cross-sectional	528 elderlies	Nighttime blood pressure	BMI, smoking, alcohol consumption, drug use, diabetes mellitus, eGFR, time to bed, duration in bed and nocturia frequency, day length, UME	Significant β for SBP = 3.922–5.395; β for DBP = 2.773–2.825/ linear regression	Obayashi et al. (2014a)
Cross-sectional	131 young adults	Circadian rhythm	Interaction between variables	Comparisons of wrist temperature due to day–night light contrast/ANOVA	Martinez-Nicolas et al. (2014)
Cross-sectional	12 M-type and 12 E-type subjects	Circadian phase[n.s]	Shift work, travelling to another time zone in the past 3 months, smoking, drug or medication, hormonal contraceptive	Comparison circadian phase angle between M-types and E-types/ANOVA	Goulet et al. (2007)
Cross-sectional	30 nurses	Phase advance and delay[n.s]	Smoking, medication, pregnancy, lactating, sleep disorders	24-h profile of light exposure of three groups (phase delayed, phase advanced, non-shift) was significantly different. but the total amount of light was not (phase delayed, phase advanced, non-shift group) was not different/ANOVA	Dumont et al. (2001)

In these observational studies, outdoor ALAN levels, individual lighting habits during sleep, and measurement values of indoor illumination level were applied as indicators of ALAN exposure.
ALAN, artificial light at night; ASR, age-standardizes rate; B or β, regression coefficient; BC, breast cancer; BMI, body mass index; DSPD, delayed sleep phase disorder; DLMO, dim light melatonin onset; CBT, core body temperature; OLS, ordinary least squares; OR, odds ration; aOR, adjusted odds-ratio; CI, confidence interval; HR, hazard ratio; 6-OHMS, 6-hydroxy melatonin sulfate; UME, urinary 6-sulfatoxymelatonin excretion; E-type, subjects of evening-type in the chronotype test; M-type, subjects of morning type in the chronotype test; eGFR, estimated glomerular filtration rate; SES, socioeconomic status; SBP, systolic blood pressure; DBP, diastolic blood pressure; MF, magnetic field.
[a]In these studies, lung cancer was a comparison target, used for emphasis, rather than acting as a confounder.
[b]Data in this table show results that were statistically significant.
[c]In this study, authors analyzed the synergistic effect of electromagnetic field and LAN exposure to melatonin production.
[n.s]Not significant variable.

TABLE 2. Experimental studies of exposure of human subjects to controlled bright light in the laboratory.

Subjects (mean age or age range)	BL control (Lux)	DL control (Lux)	Exposure time	Main statistical method applied	Significant association	References
8 males (22.0)	2800	120	From midnight (21:00) to early in the morning (04:30)	ANOVA	Melatonin concentration, rectal temperature, SBP	Yokoi et al. (2006)
5 males (20–28)	2500	<100	2 h at night	Wilcoxon matched-pairs signed ranks test, Paired t-test	Salivary melatonin, rectal temperature, sleep latency	Bunnell et al. (1992)
36 young adults (21.9)	100 for ex.1 5000 for ex. 2, 3	<10	24:00 to 04:00 for ex.1, 2 12:00 to 4:00 for ex 3	Paired t-test	Melatonin concentration, sleepiness	Rüger et al. (2005)
14 adults (22–35)	Bright white light about 3000	Dim red light <15	00:30–04:30	ANOVA	Melatonin suppression, CBT, sleep latency	Lavoie et al. (2003)
8 adults (20–53)	2000	<10	24:00–02:00	ANOVA	Melatonin concentration	Hätönen et al. (1999)
12 males (21.8)	5000	<10	24:00–04:00	ANOVA, Paired t-test	CBT, sleepiness, suppression of melatonin	Rüger et al. (2003)
10 adolescents (14–15)	2000	60	19:25–22:30	Wilcoxon test	Melatonin concentration	Harada (2004)
36 young adults (22)	2984	1.9	3 h of bright light exposure, starting 1 h prior to habitual wake time	t-test	DLMO, circadian phase shifts	Burke et al. (2013)
6 (48.6) for ex. 1 7 (23) for ex. 2	100 (green light)	<1 (red light)	23:30–00:30 in 1st session and 60 min in 2nd and 3rd session for ex. 1 60 min for ex. 2	ANOVA	Melatonin suppression, DLMO	Figueiro & Rea (2012)
16 young (29.3) and 14 older (67.1) adults	3500	10	4 h at night	ANOVA	DLMO, DLMOff	Benloucif et al. (2006)
34 young adults (21.8)	<8000	<3	1 h at night	Non-linear least-square analysis (Levenberg–Marquardt algorithm)	PRC	St Hilaire et al. (2012)
116 youth and adults (18–30)	≤200	<3	Nighttime before bedtime (ca. 24:00)	ANOVA	Melatonin suppression	Gooley et al. (2011)
23 males (22.1)	9500 (7000–13 000)	10–15	24:00–05:00	ANOVA	CBT, plasma melatonin	Shanahan et al. (1999)
48 males (23)	9500/1260/600/180/12/<0.03		5 h early biological night	Logistic model (non-linear least square analysis)	Melatonin suppression	Zeitzer et al. (2005)

Subjects (ex.)	Low light	High light	Schedule	Statistical test	Measured variables	Reference
8 adults	100	1000	18:00–08:00	ANOVA	Suppression of melatonin metabolite aMT6s	Foret et al. (1996)
10 adults (27)	Light off	40 (Light on)	23:00 to before waking	Wilcoxon signed-rank test	Sleep depth and stability	Cho et al. (2013)
7 adults (22.7)	10	2500	During 40 min before sleep onset	Wilcoxon test	Sleep latency (EEG stage)	Komada et al. (2000)
12 males (23.5)	200	2500	Evening (2h for DL; 0.5h for BL) after sunset	Paired t-test, ANOVA	Sleep latency, oral temperature	Tzischinsky & Lavie (1997)
6 males (21–35)	150	3000	19:00–21:30	t-test	Rectal temperature nadir, sleep initiation and overall sleep quality	Kubota et al. (1998)
14 adults (23.5)	1	90	During nighttime sleep (6.5 h)	ANOVA	Alertness, performance	Chang et al. (2013)
8 young adults (19–25)	<50	2000	20:00–08:00	ANOVA	Alertness, performance, suppression of melatonin metabolite aMT6s	Daurat et al. (2000)
24 males (23.1)	<10	<5000	Daytime experiment: 12:00–16:00 Nighttime experiment: 00:00–4:00	*Post-hoc* ANOVA	Heart rate, CBT	Rüger et al. (2006)
8 males (22.0)	120	2800	21:00–04:30	ANOVA	Skin/rectal temperature, sleepiness, Theta/alpha wave activity	Yokoi et al. (2003)
9 females (21.0)	200	5000	18:00–20:00	Wilcoxon signed-rank test	Heart rate variability	Kohsaka et al. (2001)
56 adults (29)	Increasing of light intensity (2000–8000)		During sleep (1, 2 or 3 h)	ANOVA	DLMO[n.s]	Dewan et al. (2011)
13 adults (22.1)	–	Extraocular light (behind the right knee) 11000	01:00–04:00	ANOVA	Phase delay, melatonin excretion, and CBT in extraocular BL exposure[n.s]	Lushington et al. (2002)
10 females (20.5)	50	2000	15:00–24:00	Paired t-test	Amount of breath hydrogen[n.s]	Hirota et al. (2010)

ex., experiment; BL, bright light; DL, dim light; SBP, systolic blood pressure; CBT, core body temperature; PMDD, premenstrual dysphoric disorder; DLMO, dim light melatonin onset; DLMOff, dim light melatonin offset; PRC, phase response curve; EEG, electroencephalographic; MBP, mean blood pressure.
[n.s]Not significant variable.

TABLE 3. Experimental studies of ALAN exposure characteristics on human health effects.

Subjects (mean age or age range)	Light intensity	Considered factor	Exposure control	Main statistical method applied	Significant association	Reference no.
39 young adults (22.2)	<10 000 Lux	Exposure duration	0.2/1.0/2.5/4.0/6.5 h during sleep	ANCOVA	Circadian timing system, melatonin suppression, sleepiness	Chang et al. (2012)
56 adults (20–40)	2000/4000/8000 Lux	Exposure duration	1–3 h during sleep	ANOVA	Magnitude of light-induced delays	Dewan et al. (2011)
30 adults (21)	>8000 Lux	Exposure duration	2/4 h at night	ANOVA	Sleep latency, performance (only with 4-h exposure)	Thessing et al. (1994)
8 young adults (19–25)	2000 Lux	Exposure duration	Short exposure (20:00–00:00 and 04:00–08:00) All night exposure (20:00–08:00)	ANOVA	Alertness, performance, melatonin level	Daurat et al. (2000)
6 adults (24.3) 17 adults (23.8)/14 adults (23.5)	1200 Lux 90 Lux	Exposure duration Photic history	Days 1–3 6.5 h at night	ANOVA ANOVA	Circadian phase shift Melatonin suppression, phase shift, alerting effects	Deacon & Arendt (1994) Chang et al. (2011, 2013)
23 adults (22.8)	6000–13 000	Exposure time	Morning exposure (08:30–13:30)/afternoon exposure (13:30–18:30)/evening exposure (18:30–23:30)	ANOVA	Phase shift delay and sleep latency in the evening exposure group	Carrier & Dumont (1995)
8 males (19–23)	700–1000 Lux	Exposure time	Evening exposure (20:00–24:00)/morning exposure (04:00–08:00)	ANOVA	Difference in rectal temperature in the evening exposure group	Foret et al. (1998)
12 adults (39.3)	2500 Lux	Exposure time/LD cycle	Evening exposure (18:00–21:00)/morning exposure (06:00–09:00)/sleep displacement	Wilcoxon signed-rank test	Melatonin concentration, body temperature	Gordijn et al. (1999)
34 adults (30.5)	450/150 Lux	LD cycle and wakefulness-sleep schedules, Prior light history	Habitual sleep time of individuals was calculated	t-test	DLMO	Wright et al. (2005)
12 adults (28.5)	15–18 Lux	LD cycle	9/6 h sleep with DL	ANOVA	Decreasing of circadian phase advance (with evening light exposure and daytime nap)	Burgess (2013)
6 males (26)	500 Lux	LD cycle	Sleep deprivation under light condition	ANOVA	Clock gene expression, melatonin concentration, cortisol level	Kavcic et al. (2011)
12 adults (22.1)	5–13 Lux	LD cycle	L:D = 16:8 and 40:8 (sleep deprived)	ANOVA	Melatonin profile[n.s]	Cajochen et al. (2003)

ALAN, artificial light at night; LD cycle, light:dark cycle; DLMO, dim light melatonin onset.
[n.s]Not significant variable.

TABLE 4. Experimental studies of light characteristics and human health effects.

Subjects (mean age or age range, years)	Light characteristic	Light conditions	Controls	Significant association	References
16 adults (23.8)/ 16 adults (23.3)	Wavelength	460 nm	555 nm	Sleepiness, performance	Rahman et al. (2014) and Lockley et al. (2006)
12 adults (25.8)	Wavelength	Filtered <460 nm and <480 nm light	Unfiltered light	Melatonin and cortisol secretion, clock gene expression, alertness, performance	Rahman et al. (2011)
22 adults (23.1)	Polychromatic evening light condition	Near-darkness/blue-depleted/blue-intermediated/blue-enhanced/bright blue-enhanced		Circadian phase	Santhi et al. (2012)
9 adults (26.3)	Light temperature	DL(<10 Lux)/Bathroom yellow (130 Lux, 2000 K)/office day-light white (500 Lux, 6000 K)/bathroom daylight white (130 Lux, 6000 K)/planon warm white (500 Lux, 2800 K)/hall daylight white (500 Lux, 5000 K)		Circadian rhythm	Wahnschaffe et al. (2013)
8 adults (32.1)	Wavelength	460 nm	640 nm	Alertness	Phipps-Nelson et al. (2009)
30 adults (25.2)	Light temperature	Blue-enriched (6500 K)/classic (3000 K)/warm (2500 K)		Sleep	Chellappa et al. (2013)
14 adults (21–46)	Wavelength	Red (630 nm) 10 and 40 Lux/blue (470 nm) 10 and 40 Lux		Circadian phase	Figueiro et al. (2009)
33 males (22.6)	Wavelength	DL(<5 Lux)/short wavelength (<530 nm; 193 Lux)/full spectrum light (256 Lux)		Circadian phase	van de Werken et al. (2013)
5 males (20.0)	Color temperature	Daylight (6500 K; 1000 Lux)/warm white (3000 K; 1000 Lux)/control (50 Lux)		Circadian phase	Morita & Tokura (1996)
94 males (20.3)	Color temperature	Low color light at night	No exposure at night	Improving melatonin secretion and sleep quality under low color light exposure	Wada et al. (2013b)

All studies except Wada et al. (2013a, b) (Kruskal–Wallis and correlation test) were applied with ANOVA for statistical method.
DL, dim light.

suppression in study subjects, in contrast to the BL condition of 1000 Lux (Foret et al., 1996), while another study reported melatonin suppression under 100-Lux conditions (Zeitzer et al., 2005). Furthermore, there are no absolute definitions for BL and DL conditions. We can assume that exposure to strong light carries more risk than exposure to low levels of light, and low levels of light than dimmer light, and dimmer light than complete darkness, especially when sleeping at night. Furthermore, even at the same level of brightness, short wavelength blue or blue-enriched light has more significant effects on the circadian rhythm. Blue light, mostly emitted from electronic devices, enhances alertness even while sleeping at night, and suppresses melatonin secretion and circadian activities.

In addition to light intensity and wavelength, the duration, cycle and time of exposure are also important in the health effects of ALAN. Some studies reported that the duration of exposure to light at night caused significant health effects, such as circadian disruption. In addition, evening light exposure before bedtime affected circadian phase more than did afternoon exposure. Thus, excessive exposure to artificial light does not involve only too bright light, but also too long or irregular exposure.

While the experimental studies reviewed in this article show acute health outcomes following light exposure, observational studies show chronic effects due to common nighttime lighting habits and exposure levels. ALAN exposure over a long period is related to an individual's lifestyle and/or dwelling characteristics. Unintended nighttime light exposure flows from light trespass in dwellings, which constitutes a form of light pollution. In areas with a high outdoor ALAN levels, light trespass is more likely to occur. If unintended ALAN exposure from the environment occurs and results in health effects, such as cancer, it is of critical significance in terms of public health. Intended ALAN exposure related to human behavioral patterns is also of significance. Particularly, many of the studies reviewed here showed that exposing children and adolescents to bright light while sleeping results in negative health effects. Many members of this age group frequently use TVs, PCs or tablet computers, mobile phones and other light-emitting (especially blue-enriched) electronic devices at night, which increases their exposure to blue light and alters biorhythms and metabolic activities, and causes sleep disorders.

Whenever intended or unintended, a bright indoor environment at night can increase the risk of cancer and circadian disruption. Furthermore, outdoor light levels, which represent nighttime activities, also represent light exposure at night and are related to cancer and circadian disruption. Outdoor illumination levels from satellite data are an index for measuring light exposure levels of regional population groups, while indoor lighting habits are an index for measuring individual exposure levels.

Health outcomes caused by ALAN

Health outcomes induced by ALAN are related to the entrainment of the biological clock. In humans and mammals, the pacemaker of the biological clock is located in the suprachiasmatic nucleus, and this is affected by the photoperiod. Therefore, many studies that investigated health effects of ALAN have reported effects on the circadian rhythm, i.e. melatonin suppression, phase shift, sleep latency and body temperature. Human health effects from ALAN exposure are based on "not dark night". Insomnia, sleep disorders and disturbances of deep sleep are induced by ALAN exposure. These outcomes may result in other, more chronic, health effects.

Circadian misalignment caused by chronic ALAN exposure may have negative effects on the psychological, cardiovascular and/or metabolic functions, as listed in Tables 1–4. ALAN exposure is regarded as an environmental stressor that can affect the immune system (Haim & Portnov, 2013). High levels of brightness and/or changes in the light environment act as a stressor to humans, especially when unintended. In addition, changes in pineal melatonin levels can affect the metabolic rate. Disruption of the circadian rhythm may lead to metabolic alterations, which may lead to obesity and/or diabetes (Haim & Portnov, 2013; McFadden et al., 2014), which has become a pandemic.

In terms of cancer effects, breast and prostate cancer may also be considered to result from chronic ALAN exposure related to lifestyle. Acute signs of circadian misalignment may develop as disease. In fact, ALAN is considered as a "modernized" phenomenon, and it may cause many "modernized" health problems. Many factors other than ALAN exposure lead to the development or exacerbation of these diseases, e.g. smoking, diet and air pollution. Nevertheless, ALAN may be considered an important risk factor given its known influence.

Limitations and conclusion

This research reviewed studies of exposure to ALAN and its assessment on health effects, as categorized by the light exposure conditions. Since this was not a meta-analysis, this review is not capable of proving the causal relationship between particular factors. Instead, this review detailed the known health effects of each risk factor. This review suggests that further meta-analysis of factor-by-outcome studies is needed to identify associations between various factors of ALAN exposure, and more diverse health outcomes are not yet clearly determined.

Although, previous papers have reviewed ALAN exposure and health outcomes, this review categorized various aspects of ALAN exposure and identified the health outcomes reported for the types of exposure. Moreover, this review assessed the effects by classification exposure as intended/unintended and acute/chronic. Light intensity, exposure duration or timing,

wavelength, individual light habits, outdoor ALAN level data obtained by satellite are also factors related to ALAN exposure conditions. However, other exposure conditions may also affect human health. For instance, flickering light at night may cause symptoms or diseases, and thus other characteristics of ALAN exposure should be determined, which will require a longitudinal study, as some diseases do not become evident over a short period.

DECLARATION OF INTEREST

The authors declare no conflicts of interests. The authors alone are responsible for the content and writing of this article.

REFERENCES

Auger RR, Burgess HJ, Dierkhising RA, et al. (2011). Light exposure among adolescents with delayed sleep phase disorder: A prospective cohort study. Chronobiol Int. 28:911–20.

Bauer SE, Wagner SE, Burch J, et al. (2013). A case-referent study: Light at night and breast cancer risk in Georgia. Int J Health Geogr. 12:23.

Benloucif S, Green K, L'Hermite-Balériaux M, et al. (2006). Responsiveness of the aging circadian clock to light. Neurobiol Aging. 27:1870–9.

Blask DE. (2009). Melatonin, sleep disturbance and cancer risk. Sleep Med Rev. 13:257–64.

Borugian MJ, Gallagher RP, Friesen MC, et al. (2005). Twenty-four-hour light exposure and melatonin levels among shift workers. J Occup Environ Med. 47:1268–75.

Bunnell DE, Treiber SP, Phillips NH, et al. (1992). Effects of evening bright light exposure on melatonin, body temperature and sleep. J Sleep Res. 1:17–23.

Burgess HJ. (2013). Evening ambient light exposure can reduce circadian phase advances to morning light independent of sleep deprivation. J Sleep Res. 22:83–8.

Burke TM, Markwald RR, Chinoy ED, et al. (2013). Combination of light and melatonin time cues for phase advancing the human circadian clock. Sleep. 36:1617–24.

Cajochen C, Jewett ME, Dijk DJ. (2003). Human circadian melatonin rhythm phase delay during a fixed sleep–wake schedule interspersed with nights of sleep deprivation. J Pineal Res. 35: 149–57.

Canton JL, Smith MR, Choi HS, et al. (2009). Phase delaying the human circadian clock with a single light pulse and moderate delay of the sleep/dark episode: No influence of iris color. J Circadian Rhythms. 7:8.

Carrier J, Dumont M. (1995). Sleep propensity and sleep architecture after bright light exposure at three different times of day. J Sleep Res. 4:202–11.

Chang AM, Santhi N, St Hilaire M, et al. (2012). Human responses to bright light of different durations. J Physiol. 590: 3103–12.

Chang AM, Scheer FA, Czeisler CA, et al. (2013). Direct effects of light on alertness, vigilance, and the waking electroencephalogram in humans depend on prior light history. Sleep. 36: 1239–46.

Chang AM, Scheer FA, Czeisler CA. (2011). The human circadian system adapts to prior photic history. J Physiol. 589: 1095–102.

Chellappa SL, Steiner R, Oelhafen P, et al. (2013). Acute exposure to evening blue-enriched light impacts on human sleep. J Sleep Res. 22:573–80.

Chepesiuk R. (2009). Missing the dark: Health effects of light pollution. Environ Health Perspect. 117:A20–7.

Cho JR, Joo EY, Koo DL, et al. (2013). Let there be no light: The effect of bedside light on sleep quality and background electroencephalographic rhythms. Sleep Med. 14:1422–5.

Czepita D, Mojsa A, Czepita M, et al. (2012). Myopia and night lighting. Investigations on children with negative family history. Klin Oczna. 114:22–5.

Daurat A, Foret J, Benoit O, et al. (2000). Bright light during nighttime: Effects on the circadian regulation of alertness and performance. Biol Signals Recept. 9:309–18.

Davis S, Mirick DK, Stevens RG. (2001). Night shift work, light at night, and risk of breast cancer. J Natl Cancer Inst. 93: 1557–62.

Davis S, Mirick DK. (2006). Circadian disruption, shift work and the risk of cancer: A summary of the evidence and studies in Seattle. Cancer Causes Control. 17:539–45.

Deacon SJ, Arendt J. (1994). Phase-shifts in melatonin, 6-sulphatoxymelatonin and alertness rhythms after treatment with moderately bright light at night. Clin Endocrinol (Oxf). 40: 413–20.

Dewan K, Benloucif S, Reid K, et al. (2011). Light-induced changes of the circadian clock of humans: Increasing duration is more effective than increasing light intensity. Sleep. 34:593–9.

Dickerman B, Liu J. (2012). Does current scientific evidence support a link between light at night and breast cancer among female night-shift nurses? Review of evidence and implications for occupational and environmental health nurses. Workplace Health Saf. 60:273–81.

Dumont M, Benhaberou-Brun D, Paquet J. (2001). Profile of 24-h light exposure and circadian phase of melatonin secretion in night workers. J Biol Rhythms. 16:502–11.

Figueiro MG, Bierman A, Plitnick B, et al. (2009). Preliminary evidence that both blue and red light can induce alertness at night. BMC Neurosci. 10:105.

Figueiro MG, Rea MS. (2012). Preliminary evidence that light through the eyelids can suppress melatonin and phase shift dim light melatonin onset. BMC Res Notes. 5:221.

Foret J, Daurat A, Tirilly G. (1998). Effect of bright light at night on core temperature, subjective alertness and performance as a function of exposure time. Scand J Work Environ Health. 24: 115–20.

Foret J, Daurat A, Touitou Y, et al. (1996). The effect on body temperature and melatonin of a 39-h constant routine with two different light levels at nighttime. Chronobiol Int. 13: 35–45.

Gangwisch JE. (2014). Invited commentary: Nighttime light exposure as a risk factor for obesity through disruption of circadian and circannual rhythms. Am J Epidemiol. 180:251–3.

Gaston KJ, Visser ME, Hölker F. (2015). The biological impacts of artificial light at night: The research challenge. Philos Trans R Soc Lond B Biol Sci. 370:20140133.

Gooley JJ, Chamberlain K, Smith KA, et al. (2011). Exposure to room light before bedtime suppresses melatonin onset and shortens melatonin duration in humans. J Clin Endocrinol Metab. 96:E463–72.

Gordijn MC, Beersma DG, Korte HJ, et al. (1999). Effects of light exposure and sleep displacement on dim light melatonin onset. J Sleep Res. 8:163–74.

Goulet G, Mongrain V, Desrosiers C, et al. (2007). Daily light exposure in morning-type and evening-type individuals. J Biol Rhythms. 22:151–8.

Grundy A, Sanchez M, Richardson H, et al. (2009). Light intensity exposure, sleep duration, physical activity, and biomarkers of melatonin among rotating shift nurses. Chronobiol Int. 26: 1443–61.

Haim A, Portnov BA. (2013). Light pollution as a new risk factor for human breast and prostate cancers. Dordrecht, Heidelberg, New York, London: Springer.

Haim A, Zubidat AE. (2015). Artificial light at night: melatonin as a mediator between the environment and epigenome. Philos Trans R Soc Lond B Biol Sci. 370:20140121.

Harada T. (2004). Effects of evening light conditions on salivary melatonin of Japanese junior high school students. J Circadian Rhythms. 2:4.

Hätönen T, Alila-Johansson A, Mustanoja S, et al. (1999). Suppression of melatonin by 2000-Lux light in humans with closed eyelids. Biol Psychiatry. 46:827–31.

Hirota N, Sone Y, Tokura H. (2010). Effect of evening exposure to bright or dim light after daytime bright light on absorption of dietary carbohydrates the following morning. J Physiol Anthropol. 29:79–83.

Hood B, Bruck D, Kennedy G. (2004). Determinants of sleep quality in the healthy aged: The role of physical, psychological, circadian and naturalistic light variables. Age Ageing. 33:159–65.

Hurley S, Goldberg D, Nelson D, et al. (2014). Light at night and breast cancer risk among California teachers. Epidemiology. 25: 697–706.

Hurley S, Nelson DO, Garcia E, et al. (2013). A cross-sectional analysis of light at night, neighborhood sociodemographics and urinary 6-sulfatoxymelatonin concentrations: Implications for the conduct of health studies. Int J Health Geogr. 12:39.

Juutilainen J, Kumlin T. (2006). Occupational magnetic field exposure and melatonin: Interaction with light-at-night. Bioelectromagnetics. 27:423–6.

Kantermann T, Roenneberg T. (2009). Is light-at-night a health risk factor or a health risk predictor? Chronobiol Int. 26:1069–74.

Kavcic P, Rojc B, Dolenc-Groselj L, et al. (2011). The impact of sleep deprivation and nighttime light exposure on clock gene expression in humans. Croat Med J. 52:594–603.

Kloog I, Haim A, Stevens RG, et al. (2008). Light at night co-distributes with incident breast but not lung cancer in the female population of Israel. Chronobiol Int. 25:65–81.

Kloog I, Haim A, Stevens RG, et al. (2009). Global co-distribution of light at night (LAN) and cancers of prostate, colon, and lung in men. Chronobiol Int. 26:108–25.

Kloog I, Portnov BA, Rennert HS, et al. (2011). Does the modern urbanized sleeping habitat pose a breast cancer risk? Chronobiol Int. 28:76–80.

Kloog I, Stevens RG, Haim A, et al. (2010). Nighttime light level co-distributes with breast cancer incidence worldwide. Cancer Causes Control. 21:2059–68.

Kohsaka M, Kohsaka S, Fukuda N, et al. (2001). Effects of bright light exposure on heart rate variability during sleep in young women. Psychiatry Clin Neurosci. 55:283–4.

Komada Y, Tanaka H, Yamamoto Y, et al. (2000). Effects of bright light pre-exposure on sleep onset process. Psychiatry Clin Neurosci. 54:365–6.

Kubota T, Uchiyama M, Hirokawa G, et al. (1998). Effects of evening light on body temperature. Psychiatry Clin Neurosci. 52:248–9.

Küller R. (2002). The influence of light on circarhythms in humans. J Physiol Anthropol Appl Human Sci. 21:87–91.

Lavoie S, Paquet J, Selmaoui B, et al. (2003). Vigilance levels during and after bright light exposure in the first half of the night. Chronobiol Int. 20:1019–38.

Li Q, Zheng T, Holford TR, et al. (2010). Light at night and breast cancer risk: Results from a population-based case-control study in Connecticut, USA. Cancer Causes Control. 21: 2281–5.

Lockley SW, Evans EE, Scheer FA, et al. (2006). Short-wavelength sensitivity for the direct effects of light on alertness, vigilance, and the waking electroencephalogram in humans. Sleep. 29: 161–8.

Lushington K, Galka R, Sassi LN, et al. (2002). Extraocular light exposure does not phase shift saliva melatonin rhythms in sleeping subjects. J Biol Rhythms. 17:377–86.

Martin JS, Hébert M, Ledoux E, et al. (2012). Relationship of chronotype to sleep, light exposure, and work-related fatigue in student workers. Chronobiol Int. 29:295–304.

Martinez-Nicolas A, Madrid JA, Rol MA. (2014). Day–night contrast as source of health for the human circadian system. Chronobiol Int. 31:382–93.

McFadden E, Jones ME, Schoemaker MJ, et al. (2014). The relationship between obesity and exposure to light at night: Cross-sectional analyses of over 100 000 women in the Breakthrough Generations Study. Am J Epidemiol. 180:245–50.

Moher D, Liberati A, Tetzlaff J, Altman DG, The PRISMA Group. (2009). Preferred reporting items for systematic reviews and meta-analyses: The PRISMA Statement. PLoS Med. 6:e1000097.

Morita T, Tokura H. (1996). Effects of lights of different color temperature on the nocturnal changes in core temperature and melatonin in humans. Appl Human Sci. 15:243–6.

Nagata C, Nagao Y, Yamamoto S, et al. (2008). Light exposure at night, urinary 6-sulfatoxymelatonin, and serum estrogens and androgens in postmenopausal Japanese women. Cancer Epidemiol Biomarkers Prev. 17:1418–23.

Obayashi K, Saeki K, Iwamoto J, et al. (2013a). Exposure to light at night and risk of depression in the elderly. J Affect Disord. 151: 331–6.

Obayashi K, Saeki K, Iwamoto J, et al. (2013b). Exposure to light at night, nocturnal urinary melatonin excretion, and obesity/dyslipidemia in the elderly: A cross-sectional analysis of the HEIJO-KYO study. J Clin Endocrinol Metab. 98:337–44.

Obayashi K, Saeki K, Iwamoto J, et al. (2014a). Association between light exposure at night and nighttime blood pressure in the elderly independent of nocturnal urinary melatonin excretion. Chronobiol Int. 31:779–86.

Obayashi K, Saeki K, Iwamoto J, et al. (2014b). Effect of exposure to evening light on sleep initiation in the elderly: A longitudinal analysis for repeated measurements in home settings. Chronobiol Int. 31:461–7.

Obayashi K, Saeki K, Kurumatani N. (2014c). Association between light exposure at night and insomnia in the general elderly population: The HEIJO-KYO cohort. Chronobiol Int. 31:976–82.

O'Leary ES, Schoenfeld ER, Stevens RG, et al. (2006). Shift work, light at night, and breast cancer on Long Island, New York. Am J Epidemiol. 164:358–66.

Parry BL, Meliska CJ, Sorenson DL, et al. (2010). Increased sensitivity to light-induced melatonin suppression in premenstrual dysphoric disorder. Chronobiol Int. 27:1438–53.

Phipps-Nelson J, Redman JR, Schlangen LJ, et al. (2009). Blue light exposure reduces objective measures of sleepiness during prolonged nighttime performance testing. Chronobiol Int. 26: 891–912.

Rahman SA, Flynn-Evans EE, Aeschbach D, et al. (2014). Diurnal spectral sensitivity of the acute alerting effects of light. Sleep. 37:271–81.

Rahman SA, Marcu S, Shapiro CM, et al. (2011). Spectral modulation attenuates molecular, endocrine, and neurobehavioral disruption induced by nocturnal light exposure. Am J Physiol Endocrinol Metab. 300:E518–27.

Reiter RJ, Tan DX, Korkmaz A, et al. (2007). Light at night, chronodisruption, melatonin suppression, and cancer risk: A review. Crit Rev Oncog. 13:303–28.

Rüger M, Gordijn MC, Beersma DG, et al. (2003). Acute and phase-shifting effects of ocular and extraocular light in human circadian physiology. J Biol Rhythms. 18:409–19.

Rüger M, Gordijn MC, Beersma DG, et al. (2005). Weak relationships between suppression of melatonin and suppression of sleepiness/fatigue in response to light exposure. J Sleep Res. 14: 221–7.

Rüger M, Gordijn MC, Beersma DG, et al. (2006). Time-of-day-dependent effects of bright light exposure on human psychophysiology: Comparison of daytime and nighttime exposure. Am J Physiol Regul Integr Comp Physiol. 290:R1413–20.

Santhi N, Thorne HC, van der Veen DR, et al. (2012). The spectral composition of evening light and individual differences in the suppression of melatonin and delay of sleep in humans. J Pineal Res. 53:47–59.

Shanahan TL, Kronauer RE, Duffy JF, et al. (1999). Melatonin rhythm observed throughout a three-cycle bright-light stimulus designed to reset the human circadian pacemaker. J Biol Rhythms. 14:237–53.

Skene DJ, Lockley SW, Thapan K, et al. (1999). Effects of light on human circadian rhythms. Reprod Nutr Dev. 39:295–304.

St Hilaire MA, Gooley JJ, Khalsa SB, et al. (2012). Human phase response curve to a 1 h pulse of bright white light. J Physiol. 590:3035–45.

Stevens RG, Blask DE, Brainard GC, et al. (2007). Meeting report: The role of environmental lighting and circadian disruption in cancer and other diseases. Environ Health Perspect. 115:1357–62.

Stevens RG, Brainard GC, Blask DE, et al. (2014). Breast cancer and circadian disruption from electric lighting in the modern world. CA Cancer J Clin. 64:207–18.

Stevens RG. (2009). Light-at-night, circadian disruption and breast cancer: Assessment of existing evidence. Int J Epidemiol. 38:963–70.

Thessing VC, Anch AM, Muehlbach MJ, et al. (1994). Two- and 4-hour bright-light exposures differentially effect sleepiness and performance the subsequent night. Sleep. 17:140–5.

Tzischinsky O, Lavie P. (1997). The effects of evening bright light on next-day sleep propensity. J Biol Rhythms. 12:259–65.

van de Werken M, Giménez MC, de Vries B, et al. (2013). Short-wavelength attenuated polychromatic white light during work at night: Limited melatonin suppression without substantial decline of alertness. Chronobiol Int. 30:843–54.

Vollmer C, Michel U, Randler C. (2012). Outdoor light at night (LAN) is correlated with eveningness in adolescents. Chronobiol Int. 29:502–8.

Wada K, Nagata C, Nakamura K, et al. (2012). Light exposure at night, sleep duration and sex hormone levels in pregnant Japanese women. Endocr J. 59:393–8.

Wada K, Nakamura K, Tamai Y, et al. (2013a). Associations of urinary 6-sulfatoxymelatonin with demographics, body mass, sex steroids, and lifestyle factors in preschool Japanese children. Ann Epidemiol. 23:60–5.

Wada K, Yata S, Akimitsu O, et al. (2013b). A tryptophan-rich breakfast and exposure to light with low color temperature at night improve sleep and salivary melatonin level in Japanese students. J Circadian Rhythms. 11:4.

Wahnschaffe A, Haedel S, Rodenbeck A, et al. (2013). Out of the lab and into the bathroom: Evening short-term exposure to conventional light suppresses melatonin and increases alertness perception. Int J Mol Sci. 14:2573–89.

Wallace-Guy GM, Kripke DF, Jean-Louis G, et al. (2002). Evening light exposure: Implications for sleep and depression. J Am Geriatr Soc. 50:738–9.

Whittom S, Dumont M, Petit D, et al. (2010). Effects of melatonin and bright light administration on motor and sensory symptoms of RLS. Sleep Med. 11:351–5.

Wright Jr KP, Gronfier C, Duffy JF, et al. (2005). Intrinsic period and light intensity determine the phase relationship between melatonin and sleep in humans. J Biol Rhythms. 20:168–77.

Yang WS, Deng Q, Fan WY, et al. (2014). Light exposure at night, sleep duration, melatonin, and breast cancer: A dose–response analysis of observational studies. Eur J Cancer Prev. 23:269–76.

Yokoi M, Aoki K, Shimomura Y, et al. (2003). Effect of bright light on EEG activities and subjective sleepiness to mental task during nocturnal sleep deprivation. J Physiol Anthropol Appl Human Sci. 22:257–63.

Yokoi M, Aoki K, Shimomura Y, et al. (2006). Exposure to bright light modifies HRV responses to mental tasks during nocturnal sleep deprivation. J Physiol Anthropol. 25:153–61.

Zeitzer JM, Khalsa SB, Boivin DB, et al. (2005). Temporal dynamics of late-night photic stimulation of the human circadian timing system. Am J Physiol Regul Integr Comp Physiol. 289:R839–44.