CIRCADIAN®
ZircLight™
DynamicBlu™ Spectrum Control with
Zirc™ NightSafe™ and DaySync™ LEDs

Less than 2% blue light content at night

DaySync™ delivers over 20% blue content during the day

DAY AND NIGHT SPECIFICATIONS FOR EFFECTIVE CIRCADIAN LIGHTING

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EXECUTIVE SUMMARY

Electric light enabled us to conquer the night, but it has come at a significant cost to human health. Over the past 20 years, excess blue-rich light exposure at night, and too little light during the day, has been linked to dozens of serious health disorders caused by circadian rhythm disruption, including sleep disorders, depression, obesity, diabetes, cardiovascular disease and several hormone sensitive cancers including breast and prostate cancer. Exposure to the wrong light at the wrong time is now a well-established public health hazard [1, 2].

But what is the right light? Modern fluorescent and LED lighting provides too much blue-rich light exposure during the night, and too little blue-rich light exposure during the day. Therefore, it is important to design and specify effective **circadian lighting** which automatically switches between blue-rich daytime lighting to synchronize and strengthen circadian rhythms, and blue-free evening and nighttime lighting to prevent the harmful effects of light at night. This paper explains:

a) The key metric for assessing circadian lighting is the blue content of the light entering the cornea of the eye, and not desktop illumination in lux or foot-candles or the color temperature (CCT) or CRI used in traditional lighting design.

b) The specific wavelengths of blue light ("**circadian blue**") that must be controlled to strengthen and protect circadian rhythms and good health are 438-493nm.

c) The minimum threshold levels of blue content required for effective daytime lighting (sunrise to sunset) is 20 $\mu W/cm^2$ of 438-493nm circadian blue light.

d) The maximum safe threshold levels of blue content for evening and night lighting (sunset to sunrise) is 2 $\mu W/cm^2$ of 438-493nm circadian blue light.

In practical terms, assuming typical IES lighting illumination standards of 300-500 lux at the tabletop, circadian lighting fixtures should emit **less than 2% circadian blue** content during evening and night hours, and **more than 20% circadian blue** content during daytime hours. Lighting products which meet this standard for effective and safe circadian lighting at night can be recognized by the UL verification mark:

Less than 2% blue light content at night

a) The blue content of light entering the eye is critical for circadian health

Modern fluorescent and LED lighting has been designed for illumination quality and for energy efficiency, but unfortunately not for human health and well-being. Illumination quality measured in metrics such as desktop illumination (in lux or foot-candles), coordinated color temperature (CCT) and Color Rendering Index (CRI) are obviously important, as is energy efficiency measured in lumens/watt, but none of these metrics ensure effective circadian lighting.

The physiological and health effects of circadian lighting on humans are determined by the blue content of light entering the eye ("blue corneal irradiance" measured in $\mu W/cm^2$), and not by the illumination levels on the table or the desktop. The health and performance benefits of circadian lighting are mediated by a robust contrast between blue corneal irradiance during day versus nighttime hours.

b) A narrow band of blue light wavelengths must be controlled to strengthen and protect circadian rhythms and good health

The circadian disruption underlying the health effects of lighting occurs when a special type of blue-sensitive photoreceptors in the eye called "intrinsically photosensitive retinal ganglion cells" (ipRGCs) detect too much light at night, and too little in the day and communicate this to the suprachiasmatic nucleus (SCN) - the biological clock which regulates our circadian rhythms.

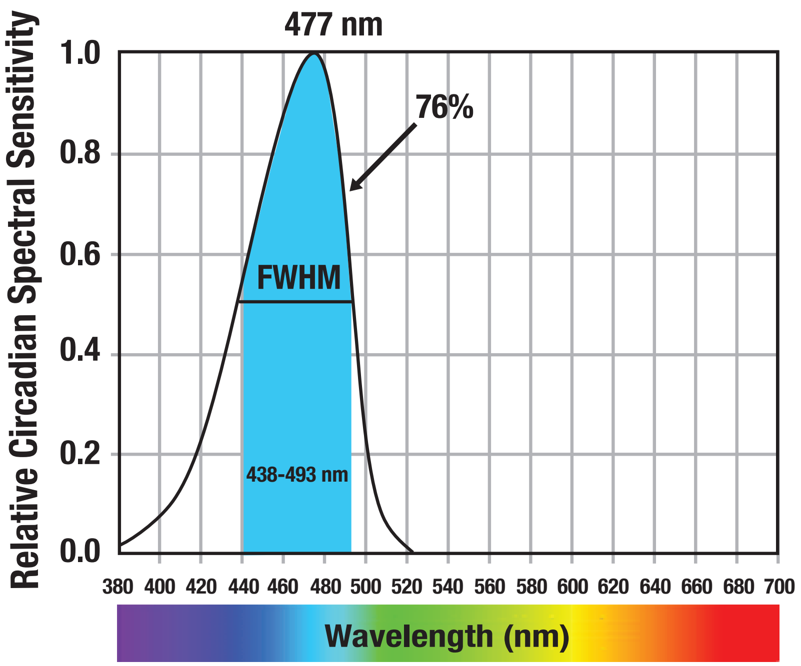

Figure 1: Circadian Blue Light: The narrow band of blue light (between 438-493nm) that synchronizes circadian rhythms during the day and disrupts them at night *(From Moore-Ede et al 2020)*

The precise light wavelengths that synchronize the human circadian clock, have been determined by studying healthy human beings under normal workplace levels of lighting for 12-hour work shifts under a variety of white LED and florescent lights with very different spectral power distributions (the mixture of color wavelengths comprising white light). This made it possible to isolate and identify a narrow human **circadian potency** spectral sensitivity curve [1] with a peak at 477nm and a full-width half-maximum of 438 to 493nm which impacts circadian rhythms under normal lighting conditions [3]. We call this band of wavelengths "**circadian blue**".

The 477nm peak color of circadian blue is not only is very close to the 479nm peak sensitivity of human melanopsin, the photopigment in the ipRGCs, but also has some very interesting significance in nature. It is the color of the clear blue sky, and the only color that penetrates the ocean depths where life began billions of year ago.

c) Effective Circadian Blue Dosage Thresholds for Day and Night

Under natural outdoor lighting conditions our circadian rhythms are kept robustly synchronized, and our sleep-wake cycles and body functions healthy, by the considerable contrast in circadian blue levels between day and night. As Figure 2 shows, the blue corneal irradiance at night even under the brightest moonlight (0.02 μW/cm²) is several thousand-fold less than the blue corneal irradiance during the normal day whether it is overcast and rainy (60 μW/cm²) or looking south with a bright blue sky (3,500 μW/cm²). In the pre-electric era natural outdoor daylight (excluding twilight and night) delivered to our eyes blue corneal irradiance levels ranging from about 20 μW/cm² on the darkest day to 7000 μW/cm² on the brightest sunny day.

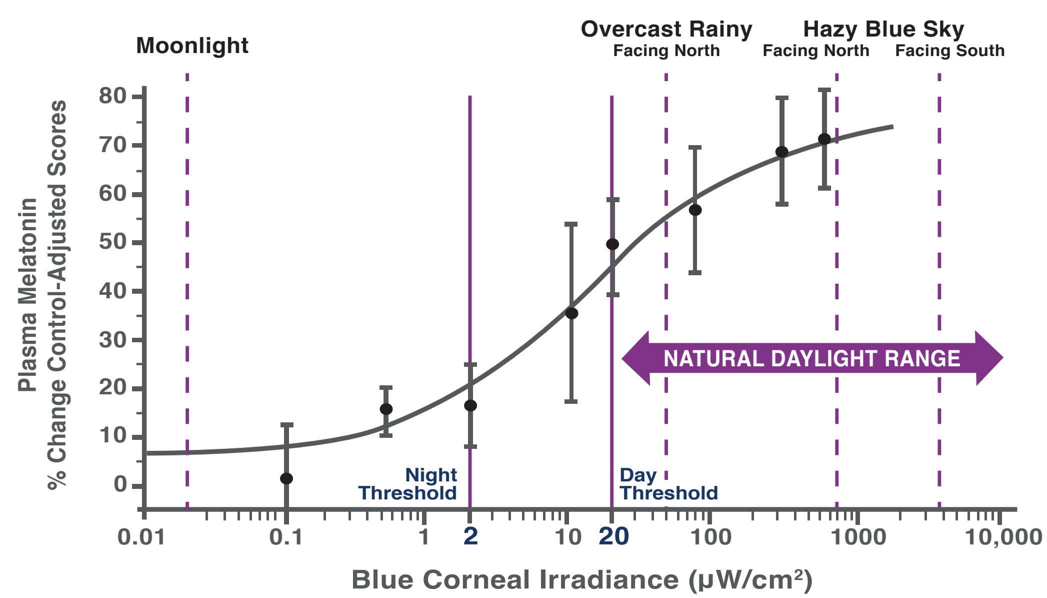

Figure 2: The Melatonin Sensitivity Curve to Circadian Blue and the Night and Day Blue Corneal Irradiance Thresholds. The blue corneal irradiance in plotted logarithmically against the degree of melatonin suppression. *(Replotted from West et al , 2011)*

[1] Previous published circadian sensitivity curves (Circadian Stimulus, Equivalent Melanopic Lux, Circadian Active Factor) were based on short (30-90 minute) exposures to mostly monochromatic (single color) lights under dark-adapted conditions, or camera flashes of light onto dark-adapted isolated retina, or human melanopsin photopigment in tissue culture. In contrast the Circadian Potency curve in Figure 1 was derived under real world workplace lighting conditions.[3]. See https://vimeo.com/428559469 for a further explanation.

The sensitivity of our circadian clocks to circadian blue light wavelengths (i.e., 438 – 493nm) can be measured using a key marker of the circadian timing system – the level of melatonin hormone released at night [4]. Minimal changes in melatonin suppression occur from the lowest levels of nocturnal light up to a blue corneal irradiance of about 2 μW/cm^2. But as levels of circadian blue light increase above 2 μW/cm^2, the impact on melatonin levels rapidly grows, reaching 50% suppression at 20 μW/cm^2. Thereafter, over the natural range of daytime illumination (20 – 7,000 μW/cm^2) the rate of change slows, reaching 70% suppression at sunny day blue corneal irradiance levels of 1000 – 7,000 μW/cm^2.

This suggests that the threshold daytime dosage levels of circadian blue that are required to ensure circadian rhythms are robustly synchronized is approximately 20 μW/cm^2, and the minimum level of circadian blue that can safely be used at night without causing circadian disruption is approximately 2 μW/cm^2.

d) Validation of the minimum threshold levels of blue content required for effective daytime circadian lighting

The melatonin response to light is a useful marker of the circadian timing system, but it is also helpful to look at studies where other meaningful outcomes such as sleep length and quality, alertness and cognitive performance have been measured at different levels of blue corneal irradiance.

Enhancing daylight exposure by spending time outdoors improves sleep quality. People exposed to daylight in offices with windows sleep significantly longer at night and have better quality night sleep than people who work in windowless offices [5]. Daytime exposure to bright blue-rich electric light increases human alertness, vigilance and performance, improves sleep quality [6,7,8,9].

By examining these studies of different daytime lighting conditions, we can determine the threshold content of circadian blue (438 – 493nm) responsible for either the beneficial or the adverse effects, and validate the threshold levels of circadian blue required for daytime lighting. This evidence summarized in Figure 3 supports the minimum daytime threshold of approximately 20 μW/cm^2 circadian blue content that is required to synchronize and stabilize the circadian system.

Lighting conditions with daytime circadian blue irradiance of less than 20 μW/cm^2 are associated with disrupted and shortened sleep, unstable circadian rhythms, depressed mood, reduced alertness and reduced cognitive performance.

In contrast, when daytime circadian blue irradiance are 20 μW/cm^2 or greater (the natural outdoor range of circadian blue) improved sleep, stable synchronized circadian rhythms, improved mood, increased alertness and improved cognitive performance have been demonstrated.

BLUE CORNEAL IRRADIANCE 438-493nm $\mu W/cm^2$	**DAYTIME CIRCADIAN LIGHTING THRESHOLD** PREVENTION OF CIRCADIAN DISRUPTION	
167	167 - *Takusa:* Synchronized circadian rhythms, increased melatonin, and daytime alertness	
‖ ‖ ‖		
100	100 - *Wakamura:* Improved sleep length and increased daytime activity	
‖ ‖ ‖		
44		
42	42 - *Boubekri:* Improved sleep length and quality, improved vitality & activity	CIRCADIAN STABILITY
40		
38		
36		
34		
32		
30		
28		
26		
24		
22	20.5 - *Viola:* Improved sleep, mood, alertness and performance	
20	20.0 - *Najjar:* Synchronized circadian rhythms; improved sleep, cognitive performance & mood	
18	**THRESHOLD**	
16		
14		
12	12.7 - *Boubekri*: Disrupted shorter sleep; lower vitality; reduced activity	CIRCADIAN DISRUPTION
10	8.4 - *Wakamura:* Reduced sleep length and decreased daytime activity	
8	8.0 - *Viola:* Impaired sleep, mood, alertness and performance	
6	5.4 - *Najjar:* Disrupted circadian sleep rhythms; impaired cognitive performance & mood	
4		
2		
1	0.3 - *Takusa:* Disrupted circadian rhythms, decreased melatonin, and daytime sleepiness	

Figure 3: The Daytime Threshold for Circadian Blue Corneal Irradiance impacts on human health and well-being

e) Validation of the maximum safe threshold levels of blue content for evening and night circadian lighting

Similarly, the sensitivity curve of the melatonin response to circadian blue corneal irradiance shown in Figure 2 suggests a threshold of 2 $\mu W/cm^2$ or less is required to prevent circadian disruption. As shown in Figure 4 this threshold is confirmed by an examination of other meaningful outcomes such as sleep length and quality, health markers such as insulin resistance and gene expression, and alertness and cognitive performance that have been measured in evening and nighttime studies where different levels of blue corneal irradiance were used [4,10-14].

BLUE CORNEAL IRRADIANCE 438-493nm µW/cm²	NIGHTTIME CIRCADIAN LIGHTING THRESHOLD PREVENTION OF CIRCADIAN DISRUPTION	
25		
24		
23		
22		
21	20.7 - *Rahman:* Suppressed melatonin, BMal1, Per2	CIRCADIAN DISRUPTION
20	20.0 - *West:* 50% suppression of melatonin	
19		
18		
17		
16		
15		
14		
13		
12	12.1 - *Munch:* Altered EEG sleep	
11	11.8 - *Moore-Ede:* Suppress & shift melatonin, increased appetite, increased insulin	
10	10.0 - *West:* 40% suppression of melatonin	
9		
8		
7	7.2 - *Kayaba:* Increased drowsiness and energy metabolism, without sleep changes	
6		
5		
4		
3	**THRESHOLD**	
2	2.0 - *West:* Minimal suppression of melatonin	CIRCADIAN STABILITY
	1.8 - *Rahman:* Restored melatonin, BMal1, Per2	
1	1.0 - *Moore-Ede:* Restored melatonin, appetite, insulin resistance	
	0.5 - *Souman:* Melatonin restored	

Figure 4: The Nighttime Threshold for Circadian Blue Corneal Irradiance impacts on human health and well-being

By examining these studies of different nighttime lighting conditions, we can determine the threshold content of circadian blue (438 – 493nm) responsible for either the beneficial or the adverse effects and validate the threshold levels of circadian blue required for nightime lighting.

This evidence summarized in Figure 4 supports the maximum evening and nighttime threshold of approximately 2 µW/cm^2 circadian blue content.

Lighting conditions with nighttime circadian blue irradiance of greater than 2 µW/cm^2 are associated with disrupted and shortened sleep, unstable circadian rhythms, melatonin suppression, disrupted circadian clock genes BMal1 and Per2, increased appetite and insulin resistance, reduced alertness and reduced cognitive performance.

In contrast, nighttime levels of circadian blue irradiance of 2 μW/cm^2 or lower, are associated with stable synchronized circadian rhythms, restoration of melatonin levels, normalized appetite and insulin resistance, normalized circadian clock genes BMal1 and Per2, improved mood, increased alertness and improved cognitive performance, and reduced errors.

Practical Guide to Circadian Lighting Specifications

The first thing to recognize that there are distinct sets of metrics used for defining illumination brightness, color and quality **versus** energy efficiency **versus** circadian efficacy as listed in Figure 5. Despite marketing claims to the contrary, color temperature (CCT) and lux levels are only weakly related to circadian efficacy and cannot be used to accurately specify circadian lighting. For example, color tuning lights which change CCT from 6500K in the day setting to 2700K in the evening setting, do not meet circadian efficacy standards because they emit 4-5 times more circadian blue content than the safe nighttime level.

ILLUMINATION METRICS	ENERGY METRICS	CIRCADIAN METRICS
Desktop Lux or Foot Candles	Lumens/watt	Blue Corneal Irradiance (μW/cm^2)
CCT (^{0}K)		% Circadian Blue in visible light (438-493 / 380-780nm)
CRI		Circadian Potency/ Photopic Ratio (CPPR)

Figure 5: The separate metrics used to specify Illumination, energy efficiency and circadian efficacy

A useful rule of thumb is that at IES standard workplace lighting levels (300-500 lux tabletop) you should specify circadian lighting sources (fixtures/bulbs) that:

1. During evening and night hours emit **less than 2% blue content** (438-493nm / 380-780nm fraction of total visible light). These will deliver the required levels of circadian blue irradiance at eye level of 2 μW/cm^2 or lower, and therefore meet the specification for safe nighttime use.
2. During daytime hours emit **at least 20% blue content** (438-493nm / 380-780nm fraction of total visible light). These will deliver the required levels of circadian blue irradiance at eye level of 20 μW/cm^2 or higher, and therefore meet the specification for healthy daytime use.
3. Change automatically between day mode (>20% blue) and night mode (<2% blue) in synch with the local sunrise and sunset adjusted for latitude and longitude and season of the year.

Lighting products which meet this standard for effective and safe circadian lighting at night can be recognized by the UL verification mark:

Less than 2% blue light content at night

UL VERIFIED verify.UL.com A097009

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ABOUT THE AUTHOR

MARTIN MOORE-EDE, M.D., Ph.D.

For over 30 years, Dr. Moore-Ede has been a leading expert on circadian clocks, and the health and safety risks faced by businesses that operate 24/7. After experiencing the challenges of fatigue as a surgeon-in-training required to work 36-hour shifts, Dr. Moore-Ede was one of the first to define the challenges of living, working, and sleeping in a 24-hours-a-day, 7-days-a-week world. As a professor at Harvard Medical School (1975–1998), he led the team that located the suprachiasmatic nucleus, the circadian biological clock in the human brain that controls the timing of sleep and wake, and pioneered research on how the human body can safely adapt to working around the clock and sustain optimum physical and mental performance.

In 1983, to implement circadian science in the workplace, Dr. Moore-Ede founded CIRCADIAN® which now helps over half of the Fortune 500 companies optimize 24/7 workforce productivity, health, and safety. In 2012, in response to the emerging evidence of the harmful effects of blue-rich LED light at night, Dr. Moore-Ede led the team that developed the first blue-depleted white LED lights for safe use at night, and established CIRCADIAN® ZircLight™, to market LED lighting systems which provide the correct blue dosage for optimal human health and safety according to the time of day, based on a comprehensive proprietary IP portfolio.

Dr. Moore-Ede graduated with a First Class Honors degree in physiology from the University of London, received his medical degrees from Guy's Hospital Medical School, and his Ph.D. in physiology from Harvard University. He has published 10 books and more than 150 scientific papers on the physiology of sleep deprivation and circadian rhythms. Dr. Moore-Ede holds multiple patents on the spectral composition of light sources, and tools for assessing and mitigating fatigue risk including the Circadian Alertness Simulator (CAS), a scientifically validated fatigue risk model. He has served on multiple national and international committees and has received numerous awards including the Bowditch Lectureship of the American Physiological Society. He is a frequent guest on television (CNN, Today Show, Good Morning America, 20:20, Dateline, Oprah Winfrey, Nova, BBC), radio (NPR Fresh Air, Connection), and print media (Wall Street Journal, New York Times, Washington Post, Time and Newsweek). He has testified before Congressional committees on multiple occasions and advised government agencies on the health and safety of the 24/7 workforce in the US, Canada, and Europe.

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