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Patient-centered lighting environments to improve health care in the intensive care unit

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Background Sleep abnormalities and disturbances of the circadian rhythm are known to negatively affect recovery for patients in the Intensive Care Unit (ICU). Daylight is the most important stimulus to entrain circadian rhythmicity by suppression of melatonin production. Therefore, light therapy seems a promising intervention to improve patients' outcome. This study examined photometric parameters of different electric light sources in the ICU.

Methods Light measurements were conducted in the ICU of a tertiary care medical centre in Germany (NCT02143661). We assessed spectral irradiance, illuminance, luminance, correlated colour temperature and colour rendering index of a fluorescent tube lamp (FL1), a fluorescent lamp with micro-lens optic (FL2) and a newly developed LED light-ceiling. Measurements were determined at patients' eye level. Spectral irradiance was assessed with a double monochromator spectroradiometer. Circadian effective irradiance was calculated by weighting the spectral irradiance with the action spectrum for melatonin suppression and by integration over all effective wavelengths.

Results The new LED light-ceiling revealed higher illuminance levels than FL1 and FL2 (1,900 to 2,750 lux vs. 260 to 750 lux and 500 to 1,400 lux). The colour rendering index was higher for the LED ceiling than both fluorescent lamps (97% vs. 74% and 77%). FL2 exceeded the threshold level of absolute glare (>10,000 candelas). The circadian effective irradiance was high for the LED ceiling compared to FL1 and FL2 (1.98 - 2.89 W/m^2 vs. 0.29 - 0.5 W/m^2 and 0.41 - 1.16 W/m^2)

Conclusion Only the newly developed LED light-ceiling provided sufficient circadian effective irradiance for maximal melatonin suppression without entering the area of absolute glare. These results should be considered when designing future health-promoting environments for critically ill patients.

doi.org/10.29102/clinhp.16002

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Introduction

Health promotion in critically ill patients is a challenge due to intensive therapy and monitoring requirements.

Sleeplessness during critical illness is one of the most frequent stressors reported by Intensive Care Unit survivors (1;2). In fact, several studies reported abnormalities of sleep quantity and quality with a significant decrease in slow wave sleep (SWS) and rapid eye movement (REM) sleep. In addition, several studies revealed that critically ill patients suffer from alterations in their circadian rhythm of melatonin production (3;4). Shigeta and colleagues found a marked increase of postoperative 24-hour melatonin patterns in ICU patients who developed delirium and additional complications (5). The reported high melatonin levels in patients with the highest severity of illness might be one possible explanation for nocturnal melatonin administration showing inconsistent results regarding clinical outcome (6;7).

Until now, nocturnal sedation was a common and widely accepted method for treating sleeplessness in the critically ill patient. However, recent studies highlighted that even small doses of sedatives impair restorative sleep (8). Additionally, sedation is associated with increased mortality and a higher risk for transitioning to delirium (9).

As a consequence of these findings, using light therapy to maintain or entrain circadian rhythm seems an adequate intervention that might have a much better risk-benefit ratio than those used in clinical routines today.

Guidelines for ICU design recommend a daylight source for every patient room and artificial light that can be dialed up

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and down to minimize circadian rhythm disruptions (10;11). But what makes a light source adequate in supporting circadian rhythmicity of a critically ill patient? Experimental data from healthy adults show that besides timing and duration, the effectiveness of light interventions in suppressing melatonin production depends on spectral irradiance, illuminance and luminance of the light source (12-16).

The primary aim of this study was to compare photometric parameters of three different electric light sources in the ICU. Furthermore, the study aimed at estimating potential circadian efficacy and side effects of the investigated light sources for exposed patients.

Methods

Light measurements (LMs) were conducted in the ICU of a tertiary care medical center in Germany. These LMs were part of an observational study, which has been registered under the ClinicalTrials.gov identifier NCT02143661. The Ethics Committee of the Charité - Universitaetsmedizin Berlin approved the study (EA1/019/14) and waived requirement for obtaining informed consent for LMs and publication of these results.

Patient room configurations, modifications and light sources

The anaesthesiologic ICU at the Charité Medical Center, where LMs took place, consists of seven 2-bed patient rooms. Patient rooms are arranged around a centrally located workstation. All rooms provide visual access to the courtyard with a window area of approximately 11 m² per room. Patient rooms 2 and 3 provide windows facing northeast whereas rooms 4 and 5 have windows facing southeast. One bed is placed on the window side and the other bed is placed on the door-side of each room (Figure 1).

Figure 1 Design and arrangement of the rooms in the intensive care unit at Charité.

Patient rooms are arranged around a centrally located workstation. All rooms provide visual access to the courtyard with a window area of approximately 11 m² per room. Patient rooms 2 and 3 provide windows facing northeast whereas rooms 4 and 5 have windows facing southeast. Marked in yellow colour are bed places were light measurements took place.

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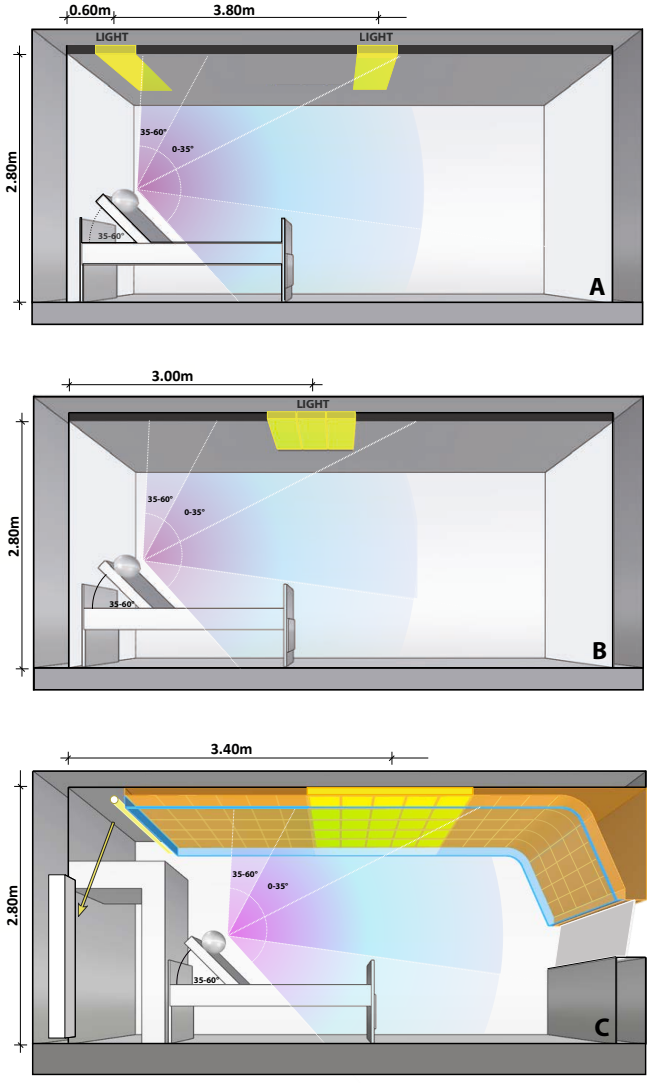
LMs in standard patient rooms with fluorescent tube ceiling lamps

The first series of LMs was performed at the window- and the door-side of patient rooms 4 and 5 on 11/26/2012, 12:30 am. Each bed place was equipped with two white light fluorescent tube ceiling lamps (FL1). The size of the radiation emitting area was 1.5 m x 0.4 m for each lamp. One of the two lamps was placed within the patient's field of view (Figure 2a).

Figure 2a-c Illustration of investigated electric light sources in ICU patient rooms.



All 2-bed patient rooms provide visual access to the courtyard with a window area of 11 m^2. (A) Two white light fluorescent tube ceiling lamps (1.5 m x 0.4 m for each lamp); (B) White light fluorescent ceiling lamp with micro-lens optic (1.5 m x 0.9 m); (C) Modified ICU room with new light-ceiling at the window-side (6.1 m x 2.4 m). The light-ceiling at the door-side bed is 4.6 m x 2.4 m. The light-ceiling integrates 2 different light-emitting diode (LED) layers: The whole area of the light-ceiling is equipped with a layer of RGB modules which have red, green and blue (RGB) LEDs. The second layer consists of white light high-performance LEDs (yellow colored area, 1.8 m x 2.4 m).

LMs in standard patient rooms with a fluorescent ceiling lamp and micro-lens optic

The second series of LMs was performed at the window-side of patient rooms 2 and 3 on 11/26/2012, 13:30 pm. Each bed place on the window-side was equipped with a white light fluorescent ceiling lamp (FL2). It included a micro-lens optic for optimising light distribution and glare control. The light output area was 1.5 m x 0.9 m (Figure 2b).

LMs in modified patient rooms with LED light-ceiling

After extensive rebuilding of patient rooms 4 and 5, a third series of LMs was performed at both bed places of the modified patient rooms 4 and 5 on 01/16/2015, 12:30pm.

The major goal of the redesigning process was to create an ICU bedroom that produces measurable improvements in the physical and psychological states of patients, visitors and staff. Beside interventions aimed at noise reduction, workflow optimisation and infection control, we conducted modifications to improve lighting conditions in the room: One integral part of the new room concept is a new light-ceiling for each bed that extends from the head above the patient down to the patient's feet. Every light-ceiling integrates two different layers of light-emitting diodes (LEDs). The first layer consists of RGB modules that have red, green and blue LEDs. The light ceiling at the window-side comprises 12,960 RGB LEDs and covers an area of 6.1 m x 2.4 m. Due to room configurations, the light-ceiling and the door-side is smaller, comprising 9,942 RGB LEDs which covers an area of 4.6 m x 2.4 m. In addition, each of the light-ceilings includes a second layer of 3,456 white light high-performance LEDs covering an area of 1.8 m x 2.4 m (Figure 2c).

Light measurements and calculation of photometric parameters

We assessed photometric light measures of the three different artificial light sources with regard to visual light effects as well as non-image-forming functions.
All LMs were determined at patients' eye level when lying with back flat on the bed (scenario 1, patient looks straight upward towards the ceiling) and when lying in bed with a head-of-bed elevation of 35 degrees (scenario 2, patient looks into the lamp).

Measurements of spectral irradiance have been carried out by means of a double monochromator spectroradiometer (type OL 754, Optronic Inc. Orlando/FL., USA), equipped with an Ulbricht sphere as optical entrance window. We used spectral steps of 1 nm, and a spectral

resolution of 1 nm within the wavelength range of 300 nm and 780 nm. Before starting the measurements, the spectroradiometer was calibrated by using a 200 W tungsten standard lamp (traceable to the National Institute of Standards Technology (NIST)), whereas wavelength calibration was performed using a ^{180}Hg-lamp.

Parameters for characterisation of visual light effects

We quantified illuminance levels (lux, lx) and luminous intensity (candela, cd/m²) of the different lighting environments. Luminance is a measure of how bright a light source is perceived. This parameter becomes especially important when using light sources with high illuminance levels as patients might experience discomfort glare when looking at it. We used a radiometer (Minilux, MX Elektronik, Berlin) equipped with a 13° tube adapter for measurements of luminance levels.

Additionally, we assessed light quality: The correlated color temperature (CCT) is a measure of the perceived color of white artificial light sources whereas the color rendering index (CRI) quantifies the capability of a light source to illuminate object colors "realistically" and "acceptably". Daylight, a reference light source in the CRI system, has a maximum CRI of 100 %.

Parameters for characterisation of non-image-forming (NIF) functions

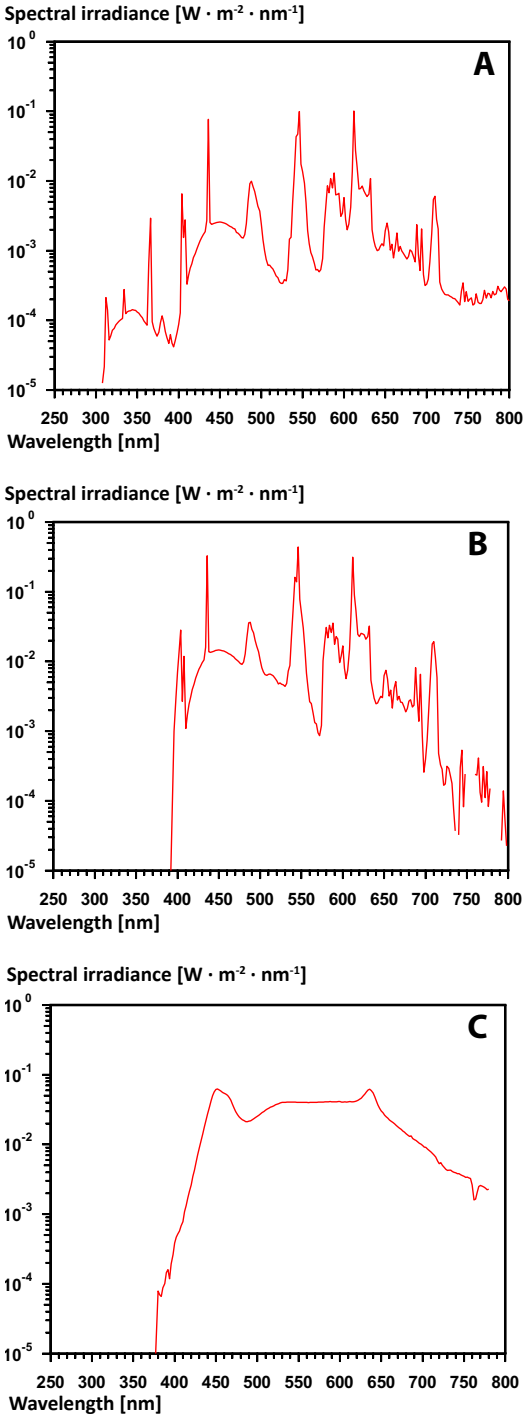
For estimation of potential circadian efficacy, we computed circadian effective irradiance (E_c) of the distinct light sources and compared values with mean thresholds for maximal melatonin suppression (healthy young adults: 0.3 W/m² and healthy people > 60 years old: 0.6 W/m²) (16).

Illuminance, circadian effective irradiance and CRI values were calculated by using measured data of spectral irradiance. These data were weighted by the spectrum of visual sensitivity of human eyes during daylight conditions and integrated over all included wavelengths. Circadian effective irradiance values were determined by weighting with the action spectrum for melatonin suppression according to Thapan et al. and Brainard et al. (12;13) which also were integrated over all included wavelengths.

Results

Both types of fluorescent lamps (FL1 and FL2) showed discontinuous spectral slopes with typical narrow band peaks in the violet, blue, green, yellow, orange and red part of the spectrum (Figure 3a-b). In contrast, the spectrum of the LED light-ceiling revealed a more balanced distribution with only two broadband peaks in the blue and the red wavelength range (Figure 3c).

Figure 3a-c Spectral irradiance of the different electric light sources.



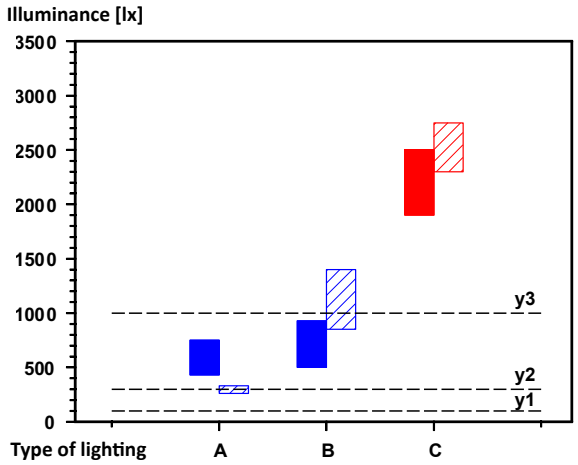
Spectral horizontal irradiance of the fluorescent lamp (FL1), the fluorescent lamp with micro-lens optic (FL2) and (C), the newly developed LED light-ceiling.

Visual light effects of the different lighting environments

Illuminance levels at bed-places equipped with FL1 ranged from 430 to 750 lx when looking straight upwards toward the ceiling and from 260 to 330 lx when looking into the lamp. FL2 revealed higher illuminance levels: 500 to 930 lx when looking straight up on the ceiling and 850 to 1,400 lx when looking towards the lamp.

The LED light-ceiling provided sufficient illuminance for medical inspection (≥1000 lx) even without looking directly into the light source (1,900 to 2,750 lx) (Figure 4).

Figure 4 Illuminance of the different light sources.



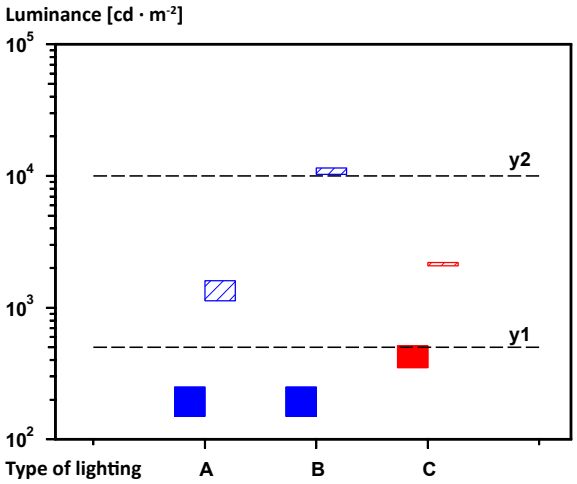
Range of measured illuminance values for the different types of lighting (see Figure 2a-c). The dashed lines indicate illuminance thresholds according to European lighting and emergency lighting standards for the Intensive Care Unit (EN DIN 12-464-1): (y1) 100 lx, threshold for accepted light level; (y2) 300 lx, threshold for reading; (y3) 1,000 lx, threshold for medical inspection. Measurements were taken at patients' eye level when lying in bed and looking straight upwards toward the ceiling (scenario 1, filled bars) and when lying in bed with a head-of-bed elevation of 35 degrees (scenario 2, bars with stripes).

For patients looking straight up on the ceiling, all of the three different light sources showed luminance levels below the threshold for relative glare (≤ 500 cd/m²).

When looking into FL2, luminance levels exceeded the threshold of absolute glare (10,000 cd/m²) ranging from 10,300 to 11,500 cd/m² (Figure 5).

Colour quality between artificial light sources differed significantly: the CCT's of FL2 (4843 K) and the LED-based light-ceiling (4606 K) were more toward the cool or blueish end of the spectrum when compared to FL1 (3907 K).

Figure 5 Luminance of the different light sources.



Range of measured luminance values for the different types of lighting (see Figure 2A-C). The dashed lines indicate luminance thresholds according to [16]: (y1) 500 cd · m^{-2}, threshold of relative glare; (y2) 10,000 cd · m^{-2}, threshold of absolute glare. Measurements were taken at patients' eye level when lying in bed and looking straight upwards toward the ceiling (scenario 1, filled bars) and when lying in bed with a head-of-bed elevation of 35 degrees (scenario 2, bars with stripes).

The CRI was 97% for the LED-based light-ceiling versus 77% and 74% for FL1 and FL 2 (Table 1).

Table 1 CCT, CRI and relative circadian efficacy for the different electric light-sources.

Type of Electric Light Source	CCT (k)	CRI (%)	k_{cv} (W · m^{-2} · klx^{-1})
Fluorecent Tube Lamp (FL1)	3907	77	0.6667
Fluorescent Lamp with micro-lens optic (FL2)	4843	74	0.8300
LED light-ceiling	4606	97	1.0419

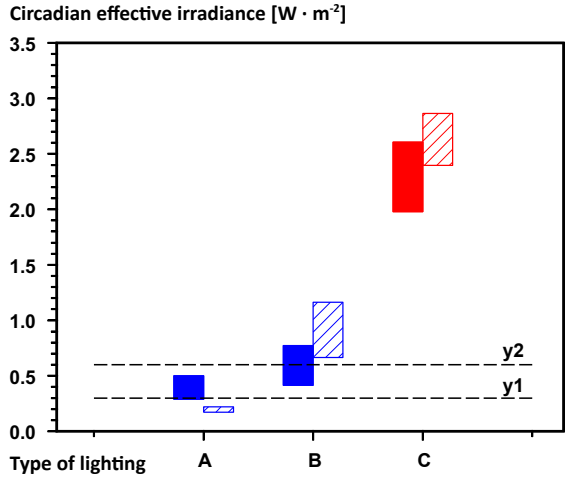
CCT, Correlated Color Temperature; k, Kelvin; CRI, Color Rendering Index; kcv, relative circadian efficacy; W, Watt; m, Meter; klx, kilolux.

Non-image-forming (NIF) effects of the different lighting environments

The circadian effective irradiance (E_c) of FL1 exceeded the mean thresholds for maximal melatonin suppression in healthy young adults when looking straight up to the ceiling. However, all calculated values for FL1 remained below the mean threshold level for maximal melatonin suppression in healthy elderly adults. FL2 revealed sufficient E_c values for melatonin suppression in healthy young adults, independently of the patient's position in bed. In contrast, E_c thresholds for the elderly were exceeded when looking straight into the new fluorescent lamp only. The E_c values of the newly

developed LED light-ceiling exceeded mean threshold for both, healthy young adults and patients > 60 years (Figure 6).

Figure 6 Circadian effective irradiance of the different light sources.



Range of measured circadian effective irradiance values for the different types of lighting (see Figure 2a-c). The dashed lines indicate the thresholds for maximal melatonin suppression [16] for (y1) healthy young adults (0.3 W · m^{-2}) and (y2) elderly adults 60 years and older (0.6 W · m^{-2}, b). Measurements were taken at patients' eye level when lying in bed and looking straight upwards toward the ceiling (scenario 1, filled bars) and when lying in bed with a head-of-bed elevation of 35 degrees (scenario 2, bars with stripes).

Discussion

This study is the first that investigated photometric parameters of lighting conditions for critically ill patients, considering both, visual as well as non-visual effects. All patient rooms showed equal configurations but were equipped with different artificial light sources. The study results showed distinct differences between characteristics of the three lighting environments, which has important implications for the design of patient-centered lighting environments in the ICU.

The European lighting standards (DIN EN 12464-1) recommend illuminance levels of at least 300 lx for simple examinations and 1,000 lx for bedside treatments and emergencies in the ICU. Our data revealed that only rooms equipped with the large LED light-ceiling provided sufficient illuminance levels at all times. Illuminance values for FL1 were below the recommended standards, even at the window side. Although FL2 showed an overall higher illuminance, measurements revealed inconsistent results: Levels of 1,000 lx could only be achieved when looking straight into the light source.

For the medical team, especially when doing invasive interventions such as central venous catheterization, the accurate illumination of object colours is important and increases patient safety. Therefore, the CRI of light sources used in the ICU should exceed 90% (DIN EN 12464-1). This specified CRI requirement was fulfilled only at bed places equipped with the LED-based light-ceiling.

Even ceiling lamps with high illuminance levels are not necessarily appropriate to provide a constant illuminance of 1,000 lx and sufficient colour rendering. In that case, portable lamps or installations of additional artificial light sources with flexible light guide arms are used in clinical practice. However, these light sources usually have a small light emitting area and very high luminance levels which probably induce significant glare in awake patients. Consequently, to avoid deep sedation and discomfort for patients, especially during invasive procedures, spotlighting with high luminance levels should be avoided and must be used with care.

We analysed NIF functions of the three lighting environments regarding potential circadian efficiency for patients treated in the corresponding ICU rooms. Exceedance of the mean threshold for maximal melatonin suppression in adults aged >60 years, was only achieved by the LED-based light-ceiling.

The circadian effective irradiance of FL2 exceeded the mean threshold level for older people as well, but only when looking straight towards the light source. However, the measured luminance exceeded the threshold of absolute glare (17) for patients looking directly at the new fluorescent lamp. One of the reasons for the observed threshold overrun is the relatively small light emitting area of FL2 compared to the LED light-ceiling.

In fact, illuminance as well as circadian effective irradiance values of the LED ceiling were more than twice as high than those measured for FL2 but without entering the zone of absolute glare. Surprisingly, patient rooms with FL1 never reached the mean threshold level of maximal melatonin suppression in healthy people aged >60 years - neither at the door nor at the window side of the room.

Data from studies performed in cohorts of non-ICU patients suggest that exposure to natural daylight significantly reduces the severity of postoperative pain (18), the length of hospital stay (19;20) and mortality (21). Within a secondary analysis of a prospective cohort study, Wunsch and colleagues compared the outcome of critically ill patients with subarachnoid haemorr-

hage treated in ICU rooms with or without windows. The authors found that the presence of a window did not improve outcome in those patients (22). In fact, LMs in the neonatal ICU revealed that illuminance of natural light entering through the window decreased considerably with distance from the window: The illuminance dropped from 550 lx directly in front of the window down to 130 lx with a 2-metre distance from the window (23). In light of these previous findings and our study results it seems unlikely that the illuminance of natural daylight from windows can trigger circadian photoentrainment in patients lying in bed with distance from the window of 1-metre or more.

A recently published randomised controlled trial showed no effect on either delirium incidence, or secondary outcome parameters of a dynamic light application therapy in the ICU (24). The lighting technology used in the study consists of the same type of fluorescent lamps (FL2) that have been evaluated in our experimental design. Simons and colleagues reported a peak illuminance level of <800 lux which is considerably lower compared to values obtained in our setting. The data indicate that the lighting system used in the study might not have been biologically effective regarding melatonin suppression.

Besides the technical specifications of the light source used, the clinical condition of the patient is essential for the effectiveness of a lighting intervention. The light needs to hit the retina to induce NIF functions, such as the suppression of pineal melatonin production. As discussed by Simons and colleagues, most of the patients in their study were sedated and had their eyes closed during the acute disease phase. This fact makes a biological effect of the used light intervention even more unlikely. Previous studies showed that high-illuminance light therapy with 10,000 lx has no effect on plasma melatonin concentrations in sedated ICU patients (25).

The fact that most critically ill patients still receive at least moderate or light sedation for a limited amount of time, emphasises that evaluation about the efficiency of specific light interventions must include a detailed reporting of daily sedation levels. Patients with light sedation (Richmond Agitation Sedation Scale (RASS) -2, briefly awakens to voice, eye-opening and contact <10 seconds) (26) might profit more from such light therapies compared to patients with moderate sedation levels (RASS -3, movement or eye opening to voice but no eye contact). Therefore, detailed documentations of daily sedation levels should be incorporated into the analysis of future lighting interventions.

Our study has the following limitations: Most importantly, we supposed mean threshold levels for relative and absolute glare as well as circadian effective irradiance measured in healthy adults to estimate the potential circadian efficiency of light sources for ICU patients. One should interpret our study results with caution as threshold levels for ICU patients might differ from those in healthy adults. Moreover, our study provides experimental data without showing clinical results that prove the efficiency of the light interventions. The next important step is to evaluate the health promoting benefits for different patient groups in the ICU.

Conclusion

The newly developed LED-based light-ceiling was the only light source which provided sufficient color rendering. Additionally, the LED ceiling exceeded thresholds for maximal melatonin suppression in young and older adults without entering the area of absolute glare. Further studies are needed to determine corresponding threshold levels for different ICU patient groups.

Key messages

- ICU patients might benefit from rooms equipped with the large LED ceilings as they provided sufficient lighting for maximal melatonin suppression without entering the area of absolute glare
- Daylight from windows did not provide adequate lighting for circadian entrainment of ICU patients
- Light sources with high illuminance levels and small light emitting areas must be used with caution as they might induce discomfort glare in patients

Acknowledgements

The authors would like to thank all nurses and physicians on the ICU for their unlimited support of the study. A very special honor and thank goes to Maria Deja, Steffen Weber-Carstens, and Andreas Sund who had a major impact in rebuilding the rooms. Ingo Fietze and Thomas Penzel from the Charité sleep center helped us with Susanne Zimmermann and Claudia Denke to identify possible targets for the redesign. We would also like to thank our project-partners Dennis Hegic, Susanne Kronfeld, Benjamin Albrecht, Ute Winninghoff, Ingrid Masswig, Jing He, Norman Wassmuth, Kai Dolata, Joachim Quantz and Joachim Sauter. The German Federation of Industrial Research Associations on behalf of the Federal Ministry of Economic Affairs and Energy financially supported the rebuilding of the ICU. Alawi Luetz is participant in the Charité Clinical Scientist Program funded by the Charité – Universitaetsmedizin Berlin and the Berlin Institute of Health.

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Authors' contributions

AL did substantial contributions to conception and design, acquisition, analysis and interpretation of data, drafting the article, revising it critically for important intellectual content and final approval of the version to be published. HP did substantial contributions to conception and design, acquisition, analysis and interpretation of data, revising the artical critically for important intellectual content and final approval of the version to be published. BW, AF, TW and CS did substantial contributions to conception and design, analysis and interpretation of data, revising the artical critically for important intellectual content and final approval of the version to be published.

Competing interests

AL, TW and CS have a patent 10 2014 215 211.9 pending. TW has a patent 10 2014 215 212.7 pending. AL and BW received personal fees from Dr. F. Köhler Chemie, and personal fees from Orion-Pharma outside the submitted work.

Outside the submitted manuscript, CS has grants from Grünenthal, grants from Dr. F. Köhler Chemie, grants from Roche, grants from MSD, grants from Orion Pharma, grants from Outcome Europe Sàrl, grants from B. Braun Melsungen, grants from AiF, grants from BDA, grants from BMBF, grants from DKH, grants from DLR, grants from German Research Society, grants from GIZ, grants from inner university grants, grants from Stifterverband, grants from European Commission, personal fees from ConvaTec International Service GmbH, personal fees from Pfizer Pharma, personal fees from Vifor Pharma, personal fees from Fresenius Kabi, personal fees from Georg Thieme Verlag. HP reports, that he has no competing interest.

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