

Patient room lighting influences on sleep, appraisal and mood in hospitalized people

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SUMMARY

Irregular 24 h light/dark cycles with night-time light exposure and a low amplitude are disruptive for sleep, mood and circadian rhythms. Nevertheless such lighting conditions are quite common in medical care facilities. A controlled clinical trial among 196 cardiology ward patients (mean age 66.5 ± 13.1 years SD) investigated how a patient room lighting intervention affects sleep, appraisal and mood across hospitalization. Patients were either assigned to a standardly-lit room or to a room with an interventional lighting system offering a dynamic 24 h light/dark cycle with low nocturnal light exposure and 2 h of bright light (1750 lux) during daytime. Measures included wrist actigraphy and questionnaires assessing alertness, sleep quality, anxiety, depression and lighting appraisal. The median length of hospitalization was 5 days in both study arms. Subjective scores on sleep, alertness, anxiety and depression did not differ between arms. Lighting appraisal in intervention rooms was better as compared to standardly-lit rooms, both in patients ($P < 0.001$) and staff ($P < 0.005$). Actigraphic sleep duration of patients improved by 5.9 min (95% CI: 0.6–11.2; $P = 0.03$ intervention $\times$ time effect) per hospitalization day with interventional lighting instead of standard lighting. After 5 days of hospitalization, sleep duration in the lighting intervention rooms increased by 29 min, or a relative 7.3%, as compared to standardly-lit rooms. A 24 h lighting system with enhanced daytime brightness and restricted nocturnal light exposure can improve some aspects of appraisal and objective sleep in hospital patients. More clinical research is needed to establish the best lighting strategy to promote healing and wellbeing within healthcare settings.

INTRODUCTION

Impaired sleep is a known hospital stressor, and hospitalized patients struggle to get sufficient sleep at night due to factors like discomfort, worries, noise, inappropriate light exposure and pain (Manian and Manian, 2015; Pisani *et al.*, 2015; Redeker and Hedges, 2002; Volicer and Bohannon, 1975). Sleep is an important factor to promote the wellbeing and recovery of patients. The human sleep–wake pattern is strongly regulated by the central circadian pacemaker

residing in the suprachiasmatic nuclei within the hypothalamus. This pacemaker uses light–dark information to initiate and control the timing, alignment and stability of the endogenous 24 h patterns in our sleep, physiology, alertness and mood. Proper timing of the light exposure is critical: brighter daytime light conditions are associated with better mood and sleep quality (Ancoli-Israel *et al.*, 2003; Boubekri *et al.*, 2014; Harrison, 2004; Lambert *et al.*, 2002; Mishima *et al.*, 2001; Riemersma-Van Der Lek *et al.*, 2008; White *et al.*, 2013), while excessive light exposure during

the evening or night-time has an acute disruptive influence on sleep (Czeisler, 2013; Santhi *et al.*, 2011; White *et al.*, 2013). The blue-light-sensitive photoreceptor pigment melanopsin (Lucas *et al.*, 2014) is an important mediator for the effects of light on our sleep–wake behaviour (Hughes *et al.*, 2015). In many healthcare facilities access to (blue-rich) daylight is limited, and current standards and guidelines for lighting systems within normal patient rooms specify horizontal illuminance thresholds in the range of 100–300 lux (CEN, 2011; IES, 2011). Consequently, the typical daytime illuminance indoors is insufficient to generate the same benefits as the outdoor illuminance (2000–100 000 lux of blue-rich light) under which we have evolved. Daytime exposure to high illuminances, from either sunlight or a few hours of bright-light therapy, is known to have beneficial effects on clinical parameters such as recovery, length of stay (LOS), delirium, depression, anxiety and use of pain medication (Beauchemin and Hays, 1998; Benedetti *et al.*, 2001; Bernhofer *et al.*, 2014; Taguchi *et al.*, 2007; Tuunainen *et al.*, 2004; Walch *et al.*, 2005; Youngstedt and Kripke, 2007). Moreover, in neonatal intensive care units cycled lighting has a favourable influence on many outcomes as compared to 2 h dimmed light or continuous light (Morag and Ohlsson, 2013). In people with dementia, night-time sleep increased significantly after 3 weeks of exposure to either morning or all-day bright light (Sloane *et al.*, 2007). Moreover, a single 2-h bright-light pulse in the morning advances the circadian rhythm (Minors *et al.*, 1991) and can help prevent sleep-compromising delays of the body clock.

Cardiovascular disease continues to be a major burden for healthcare in Europe, with close to 2500 annual hospital discharges per 100 000 inhabitants, costing €106 billion annually, of which 49% is for inpatient hospital care (Nichols *et al.*, 2012). The optimization of patient room lighting conditions can help to alleviate this burden. Therefore, we examined the effects of a dynamic patient room lighting cycle on sleep, appraisal and mood during hospitalization on a cardiology ward. Patients either stayed in control rooms with standard lighting or in intervention rooms equipped with a new dynamic lighting system. The light intensity and spectral composition in the intervention rooms are automatically tuned to generate a dynamic 24 h lighting rhythm with two late-morning hours of bright, blue-enriched white light, and low light exposure during evenings and at night-time. Wrist actigraphy was used to assess total sleep duration (TSD) and sleep-onset latency (SOL). Subjective ratings were used to evaluate sleepiness, sleep quality, headache, eye-strain, depression, anxiety, and lighting appraisal.

MATERIALS AND METHODS

Study design

From the 15th of December 2009 until the 15th of September 2010, 196 patients of the cardiology ward of the Maastricht University Medical Center (MUMC) in the Netherlands

participated in the study. All study participants gave written informed consent, and the protocol was approved by the local Medical Ethics Committee of the Maastricht University Medical Center. Patients were assigned to either a control room with standard (fluorescent) lighting conditions or to an intervention room in which the fluorescent general lighting had automated gradual changes in illuminance and correlated colour temperature (3000–6500 K) across the day, offering a dynamic 24 h light/dark cycle with low nocturnal light exposure, bright, blue-enriched white light (1750 lux, 6500 K) between 10:30 and 12:30 hours, and a 45-min post-lunch illuminance of 100 lux (3000 K) on the bed. Details of the lighting conditions are given in Fig. 1 and in Data S1.

The study was initiated as a fully randomized controlled clinical trial. However, the high occupancy of the ward forced us to abandon randomization. It appeared impossible to secure the simultaneous availability of one empty bed in both the intervention- and control-condition on sufficient inclusion moments. Instead, room assignments were done by regular hospital staff, based on room availability and routinely used hospital procedures, irrespectively of health status and fully out of reach of the investigators. The cardiologist and the resident-cardiologist supervising the ward determined the discharge date of a patient. The staff were not aware of the study assessments and acted fully independently, without any relation to the study; neither in the preparation, nor in the execution, nor in the analysis.

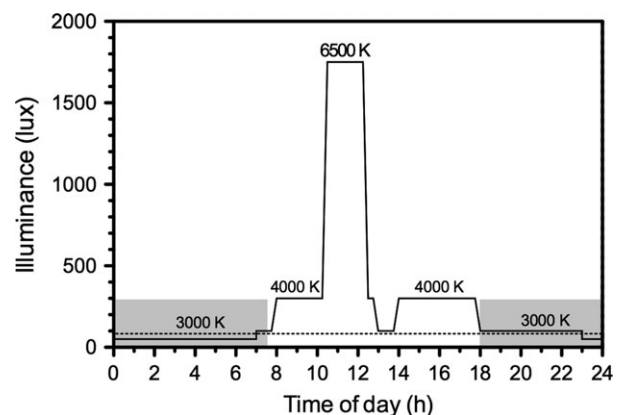


Figure 1. Schematic representation of the typical 24 h profile in general lighting within intervention rooms (solid line) and control rooms (dashed). The y-axis gives the horizontal illuminance on the bed, and the corresponding correlated colour temperatures (CCT) are indicated in the figure. The grey area indicates the evening and night-time hours with manual (de)activation of the general lighting and reading light usage. The reading light in control rooms is undimable and delivers 300 lux horizontal illuminance on the bed. Intervention rooms have a dimmable reading light, with a maximum illuminance of 300 lux. Between 23 h and 7 h, the general lighting within intervention rooms, when activated, delivers 50 lux on the bed with a CCT of 3000 K. The general lighting in control rooms, when activated, always delivers 100 lux on the bed with a CCT of 3000 K.

Study assessments

The study probed patient expectations at intake, and made daily assessments of actigraphic sleep, Hospital Anxiety and Depression Scale (HADS), Karolinska Sleepiness Scale (KSS), Headache and Eye-Strain (HES) symptoms. The Pittsburgh Sleep Quality Index (PSQI) was completed at study intake and discharge, modifying all “During the past month...” questions into “During the past days...”. Lighting appraisal was probed using a seven-point Likert scale (0 = very unsatisfied, 3 = neutral, 6 = very satisfied) to answer “How satisfied are you with the lighting system in the patient rooms?”. Table 1 and the Data S1 provide more details about these assessments.

Analysis

Between-group differences in gender, smoking, intake in autumn/winter, hypertension, diabetes, depression history and discharge diagnosis were tested by means of a Chi-squared test. A Mann–Whitney test was used to assess between-group differences in expectation, appraisal and LOS. An independent, two-sided Student’s *t*-test was used to assess between-group differences in age, body mass index, heart rate, blood pressure and PSQI. The multilevel regression model is described by Eq. (1).

$$\text{Outcome}_{ij} = \beta_0 + \beta_1 * \text{HospitalDay}_{ij} + \beta_2 * \text{Intervention}_j + \beta_3 * (\text{Intervention} * \text{HospitalDay})_{ij} + \alpha_j + \varepsilon_{ij} \quad (1)$$

The time axis is represented by HospitalDay_{ij} , which indicates the number of days a patient (*j*) has spent at the hospital at any moment (*i*, expressed in days) that the

Outcome_{ij} is measured. On the hospital intake day, HospitalDay equals one. The parameter Intervention_j indicates the lighting condition of a given patient *j*. It equals 0 for control patients and 1 for intervention patients. The intercept of the model represents the Outcome parameter at baseline (i.e. for $\text{HospitalDay} = 0$, this is the last night before hospitalization), and is defined β_0 and β_2 . Within control patients the time dependency of Outcome_{ij} is described by β_1 , and in intervention patients by $\beta_1 + \beta_3$, where β_3 represents the intervention $\times$ time interaction. In Eq. (1), α_j represents the patient-dependent (random) part of the intercept, and ε_{ij} represents the error term.

The model parameters were assessed for two cases. The first case used all available data. The second case only used the data collected during the first 5 days (and 5 nights) of the hospitalization period (i.e. $\text{HospitalDay} \leq 5$). This allows to evaluate the robustness of the model and its effect sizes when the follow-up time is restricted to the median LOS of 5 days. Simultaneously, it provides extra information on how the effect-estimates develop over time. Regression coefficients were tested for significance ($P < 0.05$) with the Wald test. The *P*-values are two-tailed.

RESULTS

In total, 580 cardiology ward patients were considered for inclusion in the study. At study closure 196 participants (mean age 66.5 ± 13.1 years SD) were enrolled (Fig. 2). Table 2 provides more information on the characteristics of the study participants. Two intervention patients discontinued their participation: one due to migraine complaints induced by the interventional lighting; and one due to actiwatch-induced skin irritation. No patient dropped out of the study due to death. The analyses were done within a homogeneous patient population, excluding all patients for which the discharge diagnosis differed from coronary artery disease or heart failure and those patients that only stayed for one night. More details on the characteristics of the various subsamples within this study are provided in the Data S2.

At study intake, patient expectations regarding effects of the lighting system on visual comfort, mood, performance, alertness, vitality, concentration and sleep quality did not differ between control and intervention patients ($P > 0.14$).

Length of stay

The median LOS [$\pm$ interquartile range (IQR)] was 4.5 (± 3) days in control patients and 5 (± 5) days in intervention patients, without a between-group difference ($z = -0.23$, $P = 0.82$). The largest LOS was 19 days.

Lighting appraisal

Scores on satisfaction with the lighting were analysed for 90 patients and 36 nursing-staff members. Median satisfaction

Table 1 Study assessments, and their timing and analysis

Assessment	Timing of assessment	Statistical analysis
Expectations	Patient intake	Mann–Whitney test
Lighting appraisal*	Patient discharge	Mann–Whitney test
LOS	Hospital discharge	Mann–Whitney test
PSQI	Patient intake and discharge	Independent Student’s <i>t</i> -test
Actigraphic sleep	Daily	Multilevel regression
HADS	Daily at 13:00 hours	Multilevel regression
KSS	Daily at 09:00, 11:00, 13:00 and 15:00 hours	Multilevel regression
HES	Daily at 11:00 hours	Multilevel regression

Multilevel linear regression analyses were performed with MLwiN software (MLwiN 2.23; Centre for Multilevel Modeling, Institute of Education, London, UK) and with Stata (StataCorp, 2013). HADS, Hospital Anxiety and Depression Scale; HES, Headache and Eye-Strain questionnaire; KSS, Karolinska Sleepiness Scale; LOS, length of stay; PSQI, Pittsburgh Sleep Quality Index.

*This questionnaire was also used in staff: once before and once after the installation of the lighting intervention.

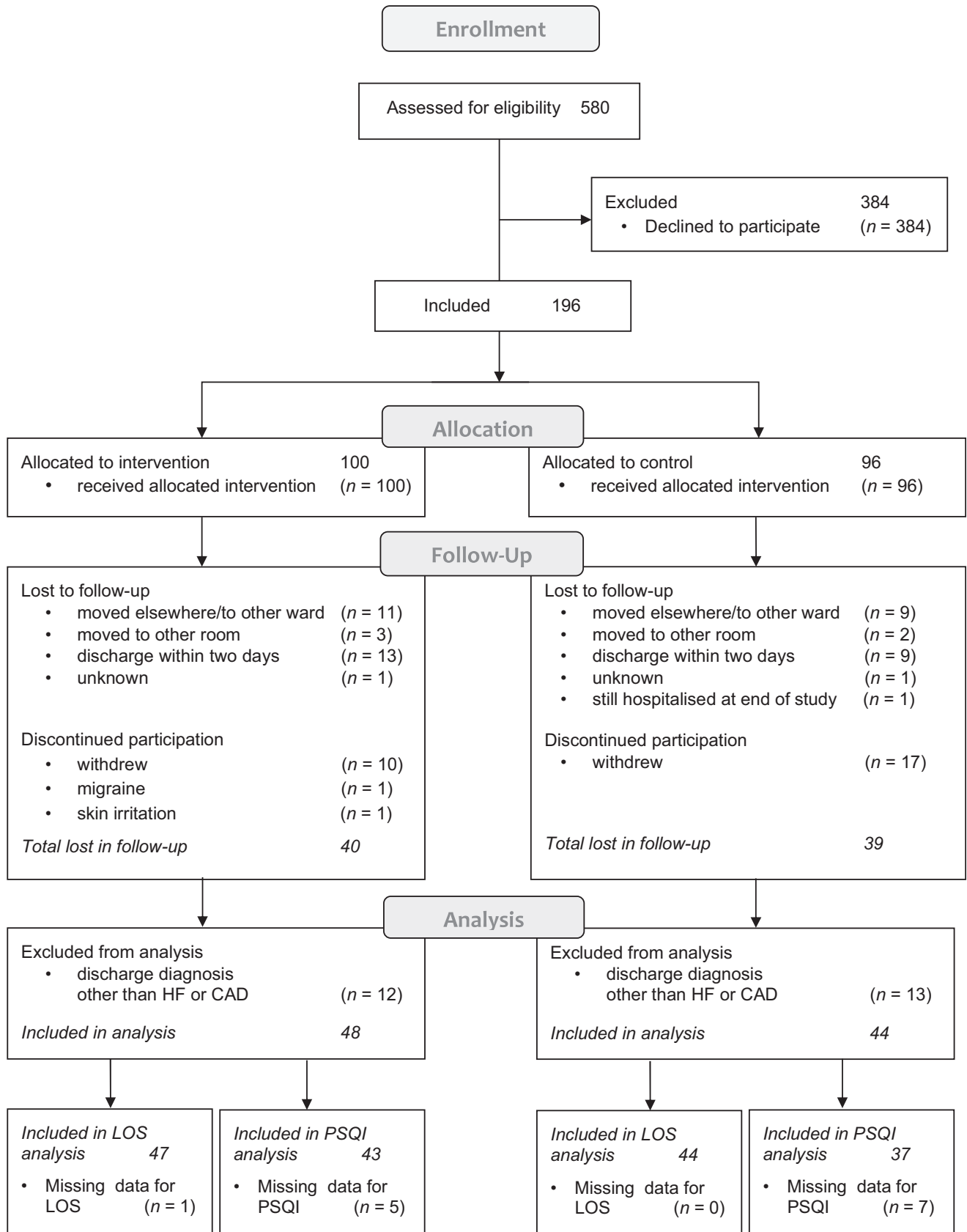


Figure 2. Flow of participants included in the study.

Table 2 Characteristics of the study intake population in the control and intervention groups

	Intervention group (n = 100)	Control group (n = 96)	P-value
Age (years), mean $\pm$ SD	68.1 $\pm$ 12.2 (n = 100)	64.9 $\pm$ 13.9 (n = 96)	0.09
Female	34 (n = 100)	27 (n = 96)	0.38
Body mass index (kg m ⁻²), mean $\pm$ SD	27.6 $\pm$ 5.5 (n = 98)	27.5 $\pm$ 5.6 (n = 95)	0.95
Heart rate (bpm), mean $\pm$ SD	75.5 $\pm$ 16.2 (n = 58)	79.3 $\pm$ 26.2 (n = 56)	0.36
Blood pressure diastolic (mmHg), mean $\pm$ SD	75.6 $\pm$ 12.5 (n = 80)	72.6 $\pm$ 14.0 (n = 82)	0.14
Blood pressure systolic (mmHg), mean $\pm$ SD	129.9 $\pm$ 18.9 (n = 80)	122.3 $\pm$ 18.1 (n = 82)	0.01
Active smoking	11 (n = 98)	20 (n = 92)	0.05
Diabetes	28 (n = 96)	17 (n = 91)	0.09
Hypertension	46 (n = 95)	43 (n = 94)	0.71
Depression history	28 (n = 98)	37 (n = 92)	0.09
Hospital admission in autumn/winter (Sept. 21st - March 21st)	68 (n = 100)	69 (n = 96)	0.55
Coronary artery disease discharge diagnosis	41 (n = 96)	46 (n = 94)	0.39
Heart failure discharge diagnosis	35 (n = 96)	28 (n = 94)	0.33

The number of observations is given between brackets. The table gives the *P*-values (of the Student's *t*-tests or the Chi-squared test) that result when testing for differences between the groups.

Active smoking gives the number of patients that were active smokers in the 3 months preceding the study.

The vast majority of patients were included in the study shortly after admission from home. The number of patients coming from intensive care is expected to be very low; however, we did not record these data. Patients were bedridden, and in general had no surgery or anaesthesia (post-operative patients in principle were admitted on a different ward). Moreover, we believe that the analysis sample represents the less ill patient group. The study included a relatively large number of questionnaires, which is difficult to comply with for very ill patients. Severely ill patients were less likely to consent to the study.

Table 3 Mean subjective sleep scores and 95% confidence interval (95% CI) within control and intervention patients at study intake and hospital discharge, as evaluated by the Pittsburgh Sleep Quality Index (PSQI) global score

	Intake		Discharge		Delta = discharge – intake	
	Control	Intervention	Control	Intervention	Control	Intervention
Subjects per group	44	48	37	43	37	43
Global PSQI	7.32	8.54	7.62	8.16	0.27	–0.88
(95% CI)	(5.93–8.71)	(7.21–9.87)	(6.34–8.9)	(6.97–9.35)	(–1.00 to 1.54)	(–2.06 to 0.30)

The delta column gives the mean of the discharge – intake PSQI score of individual patients for both groups. The global PSQI score ranges from 0 to 21, a lower score indicates a better sleep quality.

($\pm$ IQR) was 5 ($\pm$ 2) and 5 ($\pm$ 1) for control and intervention patients, respectively. Intervention patients were significantly more satisfied with their lighting as compared to control patients ($z = -4.4$, $P < 0.001$). Upon installation of the new lighting, the median staff satisfaction with the lighting improved from 3.0 ($\pm$ 2) to 3.5 ($\pm$ 1). Staff satisfaction for the new lighting was significantly better ($z = -3.0$, $P < 0.005$).

Subjective sleep: PSQI scores

The global PSQI scores at intake and discharge are given in Table 3, along with the within-subject discharge minus intake score (delta) for both groups. There were no significant differences between the groups. However, subjective sleep, as judged from the delta global PSQI value, tended to improve within intervention rooms. The detailed PSQI results are presented in the Data S2.

Multilevel linear regression analyses

We evaluated several regression model extensions of Eq. (1), including a random intercept on the room level and random slopes (see Data S2). In each case where Eq. (1) yielded a significant interventional effect, we concluded that Eq. (1) provides a reasonable model for the interventional effect estimation, obviating the need for these extensions.

Objective sleep: actigraphy

Table 4 summarizes the regression results for actigraphic TSD and SOL. Figure 3 displays the raw TSD data and regression lines for the individual control- and intervention-patients. There were no significant interventional effects on the baseline effect estimates (β_2) of the regression models in Table 4. The TSD data yielded a significant interaction effect (β_3) between HospitalDay and the intervention in the 20-day

Table 4 Effect estimates of the multilevel linear regression model (Eq. 1) for the actigraphic outcomes TSD and SOL as obtained for the overall analysis (up to 20 days of hospitalization) and for the restricted analysis (up to the first 5 days of hospitalization)

	Overall analysis		First 5 days analysis	
	TSD (95% CI)	SOL (95% CI)	TSD (95% CI)	SOL (95% CI)
Baseline control group (β_0)	402.3 min (375.6–428.9)	17.9 min (11.7–24.1)	406.8 min (367.6–446.0)	12.4 min (3.1–21.7)
Baseline intervention group ($\beta_0 + \beta_2$)	401.0 min (374.7–427.4)	15.7 min (9.6–21.9)	378.0 min (338.5–417.6)	22.4 min (12.9–31.9)
Control group change over time (β_1)	–1.3 min day ^{–1} (–5.2 to 2.5)	0.2 min day ^{–1} (–0.8 to 1.1)	–3.2 min day ^{–1} (–13.5 to 7.0)	1.5 min day ^{–1} (–1.1 to 4.1)
Intervention group change over time ($\beta_1 + \beta_3$)	4.5 min day ^{–1} (0.8–8.2)	–0.7 min day ^{–1} (–1.6 to 0.3)	11.3 min day ^{–1} (1.0–21.6)	–2.8 min day ^{–1} (–5.4 to –0.2)
Intervention effect on baseline (β_2)	–1.2 min (–38.7 to 36.2) $P = 0.948$	–2.1 min (–10.8 to 6.6) $P = 0.632$	–28.8 min (–84.5 to 26.9) $P = 0.311$	10.0 min (–3.3 to 23.3) $P = 0.141$
Intervention effect on change over time (β_3)	5.9 min day ^{–1} (0.6–11.2) $P = 0.030^*$	–0.8 min day ^{–1} (–2.2 to 0.6) $P = 0.240$	14.5 min day ^{–1} (0.0–29.1) $P = 0.050$	–4.3 min day ^{–1} (–8.0 to –0.6) $P = 0.022^*$
Intervention-control, 5th hospital night ($\beta_2 + 5\beta_3$)	28.2 min (–2.0 to 58.3) $P = 0.067$	–6.2 min (–12.6 to 0.1) $P = 0.055$	43.9 min (2.7–85.0) $P = 0.037^*$	–11.6 min (–20.8 to –2.3) $P = 0.014^*$
Standard deviation of α_j	57.5	10.9	58.5	10.2
Standard deviation of ε_{ij}	70.9	18.9	70.4	18.3

The 95% confidence interval (95% CI) is given in brackets. For the interventional effect estimates β_2 and β_3 , the two-sided P -values are also given, and an asterisk (*) denotes a significant effect ($P < 0.05$).

The baseline value is the regression model estimation (Eq. 1) for the night before hospitalization (i.e. for HospitalDay = 0).

α_j represents the patient-dependent (random) part of the intercept of Eq. (1), and ε_{ij} represents the error term.

Note that the slope of the Eq. (1) regression model within control patients equals β_1 , and in intervention patients it equals $\beta_1 + \beta_3$. These coefficients are constant and do not vary among individual patients, only the intercept of the regression line depends on the individual patient. After 5 nights of hospitalization, the TSD and SOL change with respect to baseline equals $5 * \beta_1$ for control patients, and $5 * \beta_1 + 5 * \beta_3$ for intervention patients, see Eq. (1). For this change the between-group difference hence equals $5 * \beta_3$. In the overall TSD case this corresponds to 29 min.

After model adjustment, some of the patient characteristics from Table 2 influenced the coefficients of the TSD and SOL regression models, see Supporting Information Data S2. However, those characteristics did not have a significant unbalance ($P < 0.05$) between the control and intervention sample used. Therefore, the unadjusted basis model of Eq. (1) was used to estimate effect sizes.

SOL, sleep-onset latency; TSD, total sleep duration.

analysis; for every single day that a patient stays in the intervention room as compared to staying in the control room, TSD increases by an extra 5.9 min per hospital day ($P = 0.03$). When the regression analysis is restricted to the first five hospitalization days, TSD in intervention patients tends to increase by an extra 14.5 min per day ($P = 0.0503$) as compared to control patients. In the 5-day case, SOL in intervention patients decreases by an extra 4.3 min per day ($P = 0.02$) as compared to patients in the control group. Figure 4 shows how the between-group differences as predicted by the Table 4 regression models develop over time.

There were no significant interventional effects within the actigraphic sleep efficiency regression coefficients, neither for the 20-day nor for the 5-day case (see Data S2).

Sleepiness and mood symptoms

There were no significant interventional effects within the regression coefficients of the KSS and HADS data, neither

for the 20-day nor for the 5-day models. The data are presented in the Data S2.

Headache and eye-strain

The HES questionnaire probes eight items, each on a discrete four-point scale (0 = absent, 1 = slight, 2 = moderate, 3 = severe). Four items had significant interventional effects in the 20-day and 5-day regression analyses. Table 5 shows the regression effect estimates for these four items. In the 20-day analysis, the HES-items 'eye-strain' and 'eye-fatigue' had a significantly higher baseline score (i.e. more symptoms) in intervention patients as compared with control patients (the corresponding β_2 and P -values are shown in Table 5). Moreover, intervention patients developed slightly more 'difficulties concentrating' over time than control patients: in Table 5 the intervention $\times$ time effect was small but significant ($\beta_3 = 0.032$; $P = 0.034$). In the 5-day model, the interaction effect for 'difficulties concentrating' was no

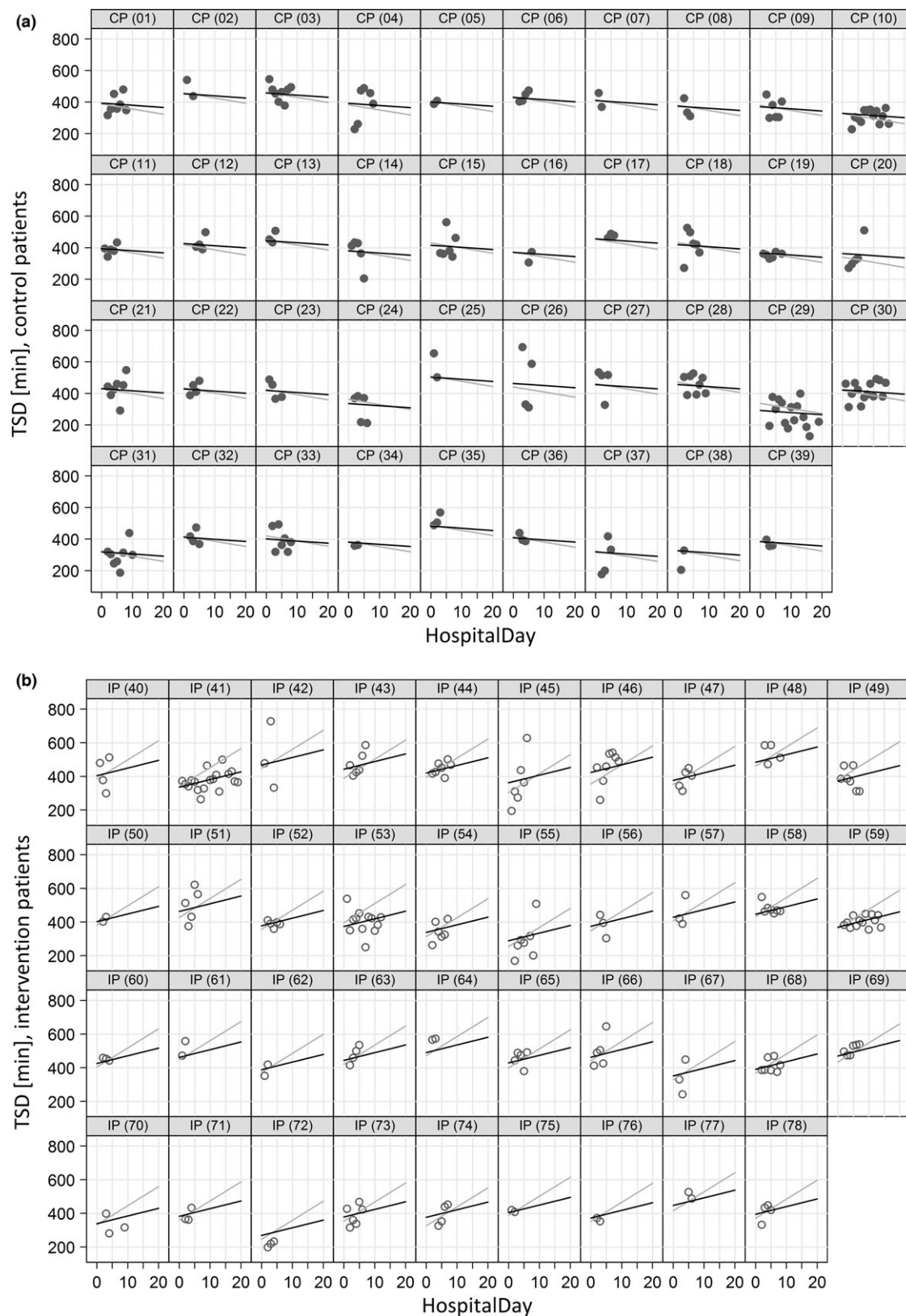
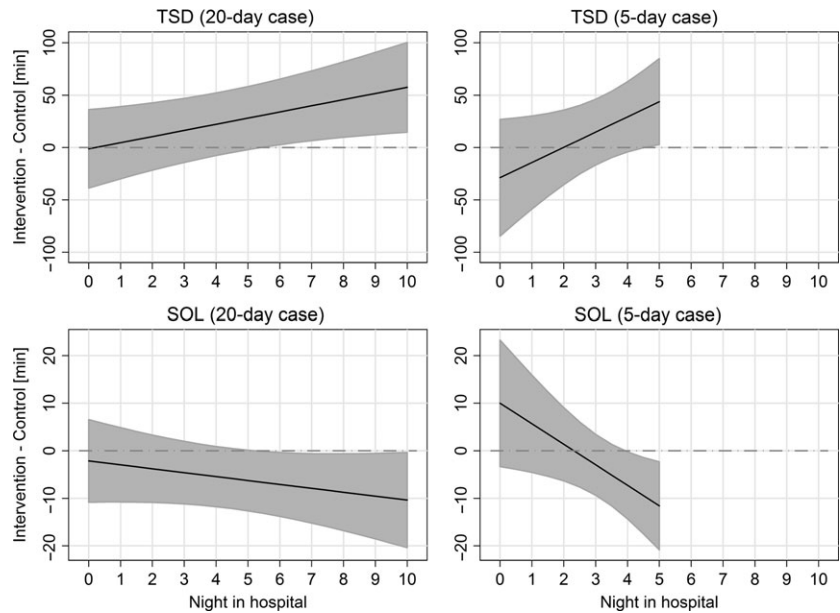


Figure 3. The actigraphic total sleep duration (TSD, in min) data-points and the corresponding regression model lines (see Eq. 1 and Table 4) of each individual patient j (denoted by the number above each panel), for the overall (20-day) analysis (black), and when restricting the analysis to the data of the first five hospitalization nights only (grey). Each panel represents a patient: (a) all control patients, CP (01-39); (b) all intervention patients, IP (40-78).

Figure 4. Multilevel linear regression predictions for the intervention–control difference in total sleep duration (TSD) and sleep-onset latency (SOL) across hospitalization in the 20-day and 5-day regression model. The model assumes that this difference changes linearly over time by $\beta_2 + \text{HospitalDay} * \beta_3$ (see Eq. 1 and Table 4). The shaded region is the 95% confidence interval. The confidence interval of the difference no longer includes zero after a few nights, only then the intervention effect on the change over time (β_3) starts to dominate over the uncertainty in the intervention effect on the baseline (β_2).



longer significant ($P = 0.56$), but here intervention patients had an extra increase over time as compared with control patients for the items ‘headache’ and ‘eye-fatigue’, the extra increases being 0.17 and 0.13 points per day, respectively. Moreover, in the 5-day model, intervention patients had a significantly lower baseline score for ‘headache’ as compared with control patients ($\beta_2 = -0.677$; $P = 0.008$).

DISCUSSION

The overall (20-day) regression model for actigraphic sleep showed a significant TSD increase by 5.9 min per hospitalization day with the new lighting system instead of standard lighting. In the 5-day regression, i.e. when only analysing data of the first five hospitalization nights, TSD increased by 14.5 min per intervention day with a P -value on the verge of significance. The confidence intervals of the model parameters for both regressions are largely overlapping. In the 20-day regression the standard error in β_3 is smaller as compared to the 5-day regression. This is likely due to the larger range in the explanatory variable ‘HospitalDay’ for the 20-day regression. Non-linearity of the changes over time can also contribute to the difference in β_3 between the 5- and 20-day regression: in the early days of hospitalization, the changes over time are expected to be larger as compared with later days where effect sizes tend to saturate. Moreover, patients with a shorter LOS might have better (health) characteristics than patients with a longer LOS, with fewer sleep-compromising medical factors, and a better ability to respond to the intervention (at least initially). Hence, a higher TSD increase per intervention day (β_3) is expected for the 5-day regression than for the 20-day regression, as is indeed observed. With the same argumentation a larger decrease in SOL per intervention day is expected for the 5-day regression than for the 20-day regression. For SOL the β_3 value differed significantly from zero only in the 5-day regression. These

findings suggest that the new lighting system is supportive for a shorter SOL. Moreover, the global PSQI score tended to improve under the new lighting system. We were unable to assess effects of the lighting intervention on daytime sleep, as many patients did not wear the actiwatch during daytime.

Regular 24 h light/dark patterns with sufficient daytime brightness, and night-time darkness (or dim light), can help health- and elderly-care residents to maintain their circadian rhythm (Beauchemin and Hays, 1998; Campbell *et al.*, 1986; Morag and Ohlsson, 2013; Ritchie *et al.*, 2015; White *et al.*, 2013; Wirz-Justice, 2007). Moreover, evening/night-time light exposure acutely suppresses melatonin production. This sleep-disruptive effect can be reduced by lowering light intensity (Brainard *et al.*, 2015; Santhi *et al.*, 2011), or by offering a preceding (daytime) exposure to bright light (Hebert *et al.*, 2002). Furthermore, 4 weeks of midday bright light are known to increase nocturnal melatonin levels in elderly insomniacs (Mishima *et al.*, 2001). In white-collar office workers, the quality of subjective nocturnal sleep was found to improve under a 4-week exposure to blue-enriched white light during daytime workhours (Viola *et al.*, 2008). As the current lighting intervention combines a low evening/night-time light exposure with two late-morning hours of bright, blue-enriched light, similar effects and mechanisms could contribute to the modest favourable influence of the current lighting intervention on sleep duration during hospitalization.

Two large-scale investigations (Choi *et al.*, 2012; Joarder and Price, 2013) found an association between brighter daytime light conditions and shorter LOS of patients. In our study we found no difference in LOS between intervention and control patients. Study participants had a mean baseline sleep duration of 401.6 min, quite similar to the 424.5 min reported by Redeker *et al.* (1998). An exploratory analysis within the current population sample indicated that a longer baseline sleep duration can act as a significant predictor for a shorter LOS (see Data S3).

Table 5 Effect estimates of the linear multilevel regression model for the four HES items that had significant interventional effects in the 20-day and 5-day analyses

	Overall analysis			
	HES eye-strain (95% CI)	HES eye-fatigue (95% CI)	HES difficulty concentrating (95% CI)	HES headache (95% CI)
Baseline control group (β_0)	0.239 (0.060–0.418)	0.421 (0.215–0.626)	0.523 (0.332–0.714)	0.472 (0.301–0.643)
Baseline intervention group ($\beta_0 + \beta_2$)	0.528 (0.353–0.702)	0.757 (0.557–0.957)	0.522 (0.335–0.708)	0.389 (0.222–0.556)
Control group change over time (β_1)	0.004 (–0.013 to 0.022)	–0.014 (–0.034 to 0.006)	–0.029 (–0.050 to –0.008)	–0.022 (–0.042 to –0.002)
Intervention group change over time ($\beta_1 + \beta_3$)	–0.010 (–0.027 to 0.007)	–0.018 (–0.038 to 0.002)	0.003 (–0.018 to 0.024)	–0.009 (–0.028 to 0.011)
Intervention effect on baseline (β_2)	0.289 (0.038–0.539) $P = 0.024^*$	0.336 (0.050–0.623) $P = 0.022^*$	–0.002 (–0.268 to 0.265) $P = 0.991$	–0.083 (–0.323 to 0.156) $P = 0.494$
Intervention effect on change over time (β_3)	–0.014 (–0.039 to 0.010) $P = 0.259$	–0.004 (–0.032 to 0.025) $P = 0.785$	0.032 (0.002–0.062) $P = 0.034^*$	0.013 (–0.015 to 0.041) $P = 0.367$
Intervention-control, 5th hospital night ($\beta_2 + 5\beta_3$)	0.218 (–0.001 to 0.437) $P = 0.051$	0.317 (0.067–0.567) $P = 0.013^*$	0.159 (–0.064 to 0.381) $P = 0.163$	–0.019 (–0.213 to 0.175) $P = 0.848$
Standard deviation of α_j	0.514	0.584	0.507	0.435
Standard deviation of ε_{ij}	0.346	0.404	0.424	0.403

The 95% confidence interval (95% CI) is given in brackets. For the interventional effect estimates (β_2 and β_3), two-sided P -values are given below the 95% CI, an asterisk (*) denotes that the parameter differs significantly ($P < 0.05$) from zero.

The HES questionnaire uses a discrete four-point scale (0 = absent, 1 = slight, 2 = moderate, 3 = severe) for eight items: irritability, headache, eye-strain, general eye-discomfort, eye-fatigue, difficulty focusing, difficulty concentrating, and blurred vision.

The baseline value is the regression model estimation for the variable in the night before hospitalization (i.e. for HospitalDay = 0).

α_j represents the patient-dependent (random) part of the intercept of Eq. (1), and ε_{ij} represents the error term.

HES, Headache and Eye-Strain questionnaire.

Multilevel linear regression models tend to overestimate the significance of effects on outcomes that are highly discrete in nature, like the HES. Nonetheless, the findings suggest that the intervention slightly affects some HES items. More studies are needed to assess the influence of lighting conditions on headache and eye-strain complaints in hospital patients.

The HADS scores in this study were close to 5 (see Data S2) and classified as 'normal', leaving little opportunity for improvements. Additional studies need to clarify whether the intervention can treat depressive patients.

Two limitations of this study are worth noting. During the study the hospital changed from paper-based to electronic registration of medication prescriptions, and prescription data could not be retrieved for nearly 20% of the patients. Prescription evaluation classified patients as users or non-users for: (1) aspirin/oral anti-coagulation; (2) anti-arrhythmic drugs; (3) psychopharmaca; (4) AT2-antagonists; (5) calcium-antagonists; (6) diuretics; (7) nitrates; (8) ACE-inhibitors; (9) beta-blocking agents. Hypnotics were used very restrictively. The two intake groups in this study as shown in Table 2 only

differed significantly for beta-blockers ($P = 0.04$), these were used more frequently in intervention patients. Beta-blockers are known to negatively impact sleep (Yamada *et al.*, 1995) and might affect the ability of a patient to respond to the intervention. Sleep in patients on beta-blockers improves under nightly melatonin administration (Scheer *et al.*, 2012). The lighting intervention could induce similar effects within patients on beta-blockers (increasing their endogenous night-time melatonin production). However, a beta-blocker-adjusted analysis for TSD (20-day case) suggests that beta-blocker users might be less responsive to the lighting intervention than beta-blocker non-users (see Data S2). This topic merits further study.

Patient inclusion in this study proceeded much slower than expected, and time and budget restrictions enforced study closure without reaching the targeted sample size. The current analysis was based on a relatively modest and incomplete dataset.

In summary, standardly-lit patient rooms did not differ in LOS as compared to patient rooms with a dynamic lighting system that provided bright daytime, and low nocturnal light exposure.

<i>First 5 days analysis</i>			
<i>HES eye-strain (95% CI)</i>	<i>HES eye-fatigue (95% CI)</i>	<i>HES difficulty concentrating (95% CI)</i>	<i>HES headache (95% CI)</i>
0.459 (0.145–0.773)	0.939 (0.582–1.296)	0.603 (0.238–0.967)	0.922 (0.565–1.279)
0.534 (0.226–0.842)	0.790 (0.439–1.140)	0.567 (0.210–0.925)	0.245 (–0.106 to 0.596)
–0.051 (–0.122 to 0.019)	–0.151 (–0.230 to –0.071)	–0.045 (–0.131 to 0.041)	–0.138 (–0.224 to –0.053)
–0.008 (–0.079 to 0.064)	–0.021 (–0.101 to 0.059)	–0.009 (–0.095 to 0.078)	0.034 (–0.052 to 0.120)
0.074 (–0.366 to 0.514)	–0.150 (–0.650 to 0.350)	–0.035 (–0.546 to 0.475)	–0.677 (–1.177 to –0.176)
<i>P</i> = 0.741	<i>P</i> = 0.557	<i>P</i> = 0.892	<i>P</i> = 0.008*
0.044 (–0.057 to 0.144)	0.130 (0.017–0.243)	0.036 (–0.085 to 0.158)	0.172 (0.051–0.294)
<i>P</i> = 0.393	<i>P</i> = 0.024*	<i>P</i> = 0.558	<i>P</i> = 0.005*
0.293 (0.026–0.560)	0.501 (0.192–0.810)	0.147 (–0.138 to 0.431)	0.185 (–0.083 to 0.452)
<i>P</i> = 0.031*	<i>P</i> = 0.002*	<i>P</i> = 0.313	<i>P</i> = 0.176
0.527	0.621	0.513	0.454
0.372	0.417	0.456	0.458

Also, subjective sleep (PSQI), and anxiety and depression scores (HADS) were not different between the conditions. The lighting intervention resulted in some improvements in objective (actigraphic) sleep and lighting appraisal within hospitalized patients. Concurrently, the subjective sleep of intervention patients, as judged from the global PSQI scores, had a tendency to improve during hospitalization. The application of lighting conditions to shape healthcare facilities that support health and wellbeing, both for patients and staff, merits further research, thus developing lighting strategies that enable hospital environments to become less disruptive for sleep, mood and circadian rhythms.

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AUTHOR CONTRIBUTIONS

LMG, MV, PL, GJBMM, HH and LJMS defined the study. LMG and MV carried out data collection. MCG, LMG, MV, PL, BdR, JWB, PMJCK and LJMS conducted the data analysis and interpretation. MCG, LMG, MV, HH, JWB and LJMS prepared the manuscript.

CONFLICT OF INTEREST

Philips funded the study; MV, PL and PMJCK declare no further conflicts of interest; JWB received consulting fees from Philips; MCG, LMG, GJBMM, HH and LJMS are employees of Philips.

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SUPPORTING INFORMATION

Additional Supporting Information may be found online in the supporting information tab for this article:

Data S1. Methods, study design and lighting conditions.

Data S2. More analysis group characteristics, regression findings and PSQI results.

Data S3. Length of stay and its predictors.