Natural Light Property-Based LED Lighting System to Maintain Human Circadian Rhythm

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Abstract. The cyclic properties of natural light give an effect on human health, and the intensity and wavelength of natural light are known to be important factors to maintain human circadian rhythm. However, modern people who stay longer indoors are exposed to the fixed light environment of artificial lighting, resulting in circadian rhythm imbalance and subsequent sleep disturbances. In this paper, a LED lighting system that reproduces the natural light properties with day cycle is proposed to support the human circadian rhythm. To do this, the properties of natural light that keep changing were measured and analyzed every hour, and then the color temperature and wavelength ratio of natural light over time were reproduced by controlling each channel of LED lighting. In order to confirm the effect of the proposed lighting that supports maintaining a circadian rhythm, a confirmation experiment of melatonin change in the animal body was performed. The experimental results showed that the rats irradiated with the proposed lighting had an increased melatonin level by more than around 20ng/ml compared to the rats irradiated with the general lighting, thus confirming that the proposed lighting had a positive effect on sustaining the circadian rhythm.

1. Introduction
Natural light provides a constantly changing light environment according to season, time, and weather conditions [1]. Natural light has the characteristic of changing with a day cycle and it is closely related to human circadian rhythm. Circadian rhythm is a biological rhythm for adapting effectively to cope with changes in the external environment and plays an important role in the human being's day cycle of 24 hours. In addition, the wavelength and intensity of periodically changing natural light are known to be important factors for maintaining circadian rhythm [2]. These circadian rhythms are related to human health. When the circadian rhythm is disturbed, it affects the synthesis and secretion of melatonin, causing sleep disturbances and problems in the immune system. Therefore, it is necessary to preserve the habit of following the natural lights’ cycle to maintain and to improve health [3].

However, modern people with long indoor activities are experiencing problems such as circadian rhythm imbalance as they are exposed to fixed light environment from artificial lighting for an extended time [4]. Previous studies to resolve such problem partially provided the color temperatures of natural light, but failed to reproduce the cyclic properties of natural light [5].

In this paper, a natural light-based LED lighting system that reproduces the daily cyclic properties of natural light is proposed to maintain the human circadian rhythm. The natural light that changes every hour was measured using a spectrophotometer and then color temperature and wavelength properties
of natural light were analyzed and extracted over time. The color temperature and wavelength ratio properties in a day cycle were then provided to the indoor residents through LED lighting that could be controlled by each channel. The effect of the natural light-based LED lighting was confirmed through the experiment of melatonin changes in the animal body according to the application of the proposed lighting that supports the circadian rhythm.

2. Natural Light-reproducing LED Lighting System

2.1 Color Temperature and Short-wavelength Properties of Natural Light

The natural light was measured to check the properties of the natural light which are continuously changing at every moment and to extract color temperature and short-wavelength ratio by time. The properties of the natural lights were measured from sunrise (-60 min.) until sunset (+60 min.) at the rooftop of a 10-story building located at a latitude of 36.85 and longitude of 127.14. The spectrophotometer (CAS 140 CT, Instruments) that can measure spectral irradiance by wavelength (280-800nm) was used for the measurement. Figure 1 shows the measurement results of the natural light on the 1st of September 2017 (weather: clear). It represents short-wavelength (380-480nm) ratio, which is known to affect the sleep pattern of humans and color temperature of natural light, which changes at a day cycle. In addition, the color temperature and short-wavelength ratio of a general lighting are displayed together for comparison.

![Figure 1](image-url)

**Figure 1.** Properties of the color temperature and short-wavelength ratio of natural light and artificial lighting

In Figure 1, the short-wavelength (380-480nm) ratio was at a minimum of 8.4% at sunset (-30 min.), while it was a maximum of 23.9% at noon (12:00). Furthermore, the color temperature was at a minimum of 3485K at sunset (-30 min.), while it was at a maximum of 5717K at noon (12:00). However, the color temperature and the short-wavelength ratio showed an increasing tendency 30 min. before sunrise and 30 min. after sunset, but they were regarded as noises at the sunrise and sunset time zones and were excluded from natural light properties extraction. In addition, the H lighting from P company was measured and the results showed fixed light properties with the color temperature of 6800K and short-wavelength ratio of 25.4%.

2.2 Natural Light-based LED Lighting

In Figure 1 In order to reproduce the color temperature and short-wavelength ratio properties of the natural light over time, four-channel LED lighting which can be controlled by each channel was fabricated. In each channel, 500 LED light sources with a spec of 56 * 56 and with color temperatures of 3980K, 6800K, 2700K, and 5300K were applied, with the LED control module for each channel and wireless communication module for receiving lighting control packet implemented. The illumination was controlled by increasing the current by 16 from 0 to 255 per channel, with the total optical properties of 4,844 lighting control stages measured. The measurement results was confirmed that the optical property of a color temperature of 2700-6800K and short-wavelength ratio of 7.8-25.4% of the proposed lighting can be realized. The control indices of the lighting from 06:00 (AM)
until 20:00 (PM) were extracted to reproduce the day cycle of natural light. For the LED control index, the control stage of the lighting nearest the natural light was explored by comparing the short-wavelength ratio and color temperature properties of natural light in each time zone with the optical property by each control stage. The control ratio by channel at the respective stage was selected after. Table 1 represents the reproduction results of the color temperature and short-wavelength of natural light measured by time through LED lighting.

| Time       | 06:30 | 07:00 | 07:30 | 08:00 | … | 09:00 – 15:20 | … | 16:30 | 17:00 | 17:30 | … | 20:00 |
|------------|-------|-------|-------|-------|---|----------------|---|-------|-------|-------|---|-------|
| Natural Light | Short wavelength ratio | 9.9% | 14.1% | 17.1% | 19.4% | … | 22.6% | … | 16% | 12.8% | 8.8% | - |       |
|            | color temperature | 3692K | 4324K | 4726K | 5039K | … | 5500K | … | 4548K | 4126K | 3473K | - |       |
| Proposed Lighting | Short wavelength ratio | 9.9% | 14.1% | 17.1% | 19.4% | … | 22.6% | … | 16% | 12.8% | 8.8% | - |       |
|            | color temperature | 2940K | 3568K | 4126K | 4805K | … | 5674K | … | 4139K | 3461K | 2814K | 2814K |       |
|            | Control stage | (0, 128, 16, 64) | (32, 96, 48, 32) | (16, 80, 48, 48) | (80, 32, 48, 48) | … | (32, 32, 112, 16) | … | (16, 80, 48, 48) | (80, 32, 48, 48) | (96, 16, 48, 32) | (128, 0, 32, 0) |       |

LED lighting control was realized in the 06:30-09:00 and 15:30-17:30 zones to make short-wavelength ratio match the color temperature closest to the natural light based on the actual measurement data of the natural light. However, the 06:00-06:30 zone is where the intensity of illumination is prominently low, thus the lighting was made off. Meanwhile, the 09:10-15:20 zone is where the changes of optical property are meager; therefore, the average optical property of the respective zone was reflected. In addition, after 17:30, the control stage where the short-wavelength ratio was the lowest was implemented to aid in sleep.

3. Experiments and Analysis
An animal experiment was conducted to analyze the changes in melatonin in the animal body in order to confirm the effect of the proposed lighting which supports the human circadian rhythm. 20 rats were used for the experiments. During a week’s acclimatization, the lighting which reproduced the property of natural light was irradiated to the experimental animals. The rats were grouped into ten each for the experimental group and control group. Two dark cases were fabricated to block external light. The proposed lighting and general lighting were installed at the top of the dark cases. The experiment proceeded by rearing the experimental rats under the environment with the proposed lighting and the control rats under the natural lighting. The rats were irradiated with each lighting daily from 06:00 until 20:00 for two weeks’ experimental period. The changes in melatonin were measured by taking blood from the rats nine times at 23:00, 02:00, and 06:00 on the experiment starting date, after seven days, and on the completion date. The melatonin changes are shown in Figure 2.

![Figure 2. Changes in melatonin between the experimental group and control group](image-url)
For analysis of the experimental results, Melatonin's assay kit was Abcam (ab213978). Statistical analysis was performed using Prism 5.03 (GraphPad Software Inc., San Diego, Calif., USA). The melatonin changes between the experimental group and the control group on the experiment starting date (D-0) were not significant. However, there were significant differences in the melatonin changes between the experimental group and control group on the 7th day (D-7) and 14th day (D-14) of the experiment. In the experimental group where the proposed lighting was implemented, the melatonin was increased by an average of 20ng/ml compared with that on the experiment starting date. In the case of the control where the general lighting was implemented, however, there were no significant differences in the melatonin amount.

4. Conclusion and Future Study Direction

In this paper, a LED lighting system that reproduces the properties of natural light was proposed to maintain the circadian rhythm of humans. The properties of natural light were measured and analyzed using a spectrometer whereas the color temperature and wavelength ratio of the natural light that keeps on changing daily were extracted. In addition, a four-channel LED lighting that can be controlled by channel was fabricated to reproduce the properties of natural light. After that, the color temperature and short-wavelength of the natural light were realized through LED lighting. In the 06:30-9:00 and 15:30-17:30 time zones, a LED lighting that matched the short-wavelength and was nearest to the color temperature of natural light was realized. Meanwhile, in the 09:10-15:20 time zones where the changes in the properties of natural light were meager, the average light properties in the respective time zones were reproduced. Furthermore, in the zone after sunset where properties of the natural light did not exist, the LED lighting which has the minimum short-wavelength ratio was provided to aid in sleep. An animal experiment was also conducted in the environment where the proposed lighting and general lighting was categorized to confirm the effect of the proposed lighting that supports the human circadian rhythm. The experimental results showed that in the experimental group where the proposed lighting was applied, the melatonin amount that is closely related to the circadian rhythm was increased by more than an average of 20ng/ml compared with that of the control group. It was, therefore, confirmed that the proposed lighting can help in maintaining the human circadian rhythm.

It is essential to conduct research in the future to develop a natural lighting reproducing a lighting system that can correctly reproduce the short-wavelength ratio and color temperature of natural light in real-time and can realize the changes of natural light by time.

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