The Tent-type Clean Unit System Platform for Air Cleaning and Non-contact Sleep Assessment

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ABSTRACT

Sleep is important to maintain human's physiological and psychological well-being. The quality is often affected by many environmental factors, such as air dust, temperature and noise. This paper proposes a tent-type clean unit system platform (T-CUSP) to construct a high air quality sleep environment. In this approximate independent-system, the feasibility of non-contact sleep monitoring method based on gas-molecule and air-particle analysis would be evaluated. In this paper, 7 overnight sleep experiments were performed with simultaneous recording of mini PSG (EEG, EOG, and EMG) for sleep staging and actigraph for body movement. The air quality was monitored by the particle counter and fluctuation of air-borne particle. The average concentrations of PM2.5, PM10, and CO2 in the T-CUSP during sleep were 4.85±3.2 μ g/m3, 8.43±4.5 μ g/m3, and 1122±128 ppm, respectively. The air-quality of T-CUSP conform to the agreed limits in US and EU. Furthermore, the fluctuation of CO2 can reflect the behavior of subjects. 91% of CO2 rising epochs were accompanied by a significant body movement and could be identified as the "wake" stage. The short experimental results demonstrate the feasibility of constructing an air-clean environment with non-contact sleep assessment to support healthy sleep.

CCS Concepts

• **Applied computing→Life and medical science→Health care information systems;**
• **General and reference→Cross-computing tools and techniques→Measurement.**

Keywords

Tent-type clean unit system platform; Sleep environment, air quality; PM 2.5/10, CO2; Actigraph.

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1. INTRODUCTION

Sleep diseases, such as insomnia and obstructive sleep apnea, seriously affect patients' quality of life. The prevalence of insomnia symptoms is approximately 33% in the general population[1]. There are over 4% of adult men and 3% of adult women be affected by obstructive sleep apnea [2]. These sleep issues may cause daytime sleepiness, irritability, depression or anxiety.

Air particulate matter (PM) is widely regarded as a source of diseases, being more harmful to those particles with a smaller size (PM1, PM2.5, etc.). Healthy risk studies have shown a significant association between exposure to particle pollution and health risks, including premature death. Health problems may include cardiovascular effects such as cardiac arrhythmias and heart attacks and respiratory effects such as asthma attacks and bronchitis[3], [4], [5]. As this result, the World Health Organization (WHO) established guideline values for this type of particulate matter in 2005[6]. Recent studies suggest that exposure to air pollution might be associated with the severity of breathing-related sleep-disordered (e.g. sleep apnea)[7], [8], [9].

An effective way to prevent and mitigate the air particles related sleep-disordered breathing (SDB) might be to create a highly air clean environment for sleep. Using a air cleaner in a close space to avoid air particulate matter is a easy solution. However, it also brings gas-exchange (CO_2 and O_2) and the power consumption issue.

The goal of the paper is to propose a tent-type high clean unit system platform (T-CUSP) to efficiently construct a high air quality sleep environment. Due to near islolated design and dust-proof breathable sheets, this system has the advantages of clean air, gas exchange and low poser consumption. All night monitoring of air quality in the T-CUSP and the sleep data of subjects were performed. The correlation between the changes of CO_2 concentraiton in the T-CUSP and the sleep behaviors of the subjects was also investigated.

2. METHOD

2.1 Subjects

Seven overnight sleep recordings including EEG, EOG, EMG and actigraphy were obtained from 7 healthy subjects (4 males and 3 females, aged 22 ~ 33 years) for analyzing the correlation between sleep patterns and the sleep environment in the T-CUSP. All subjects were healthy and non-smokers. They had no prior history of drug or alcohol abuse, physical, psychiatric and sleep disorders. On the day of the experiment, subjects could choose the bedtime which they were used to. The physiological signals and actigraphy of subjects as well the air-borne particles and gas (CO_2) in the sleep environment were simultaneously recorded for analysis.

2.2 Tent Type Clean Unit System Platform

The CUSP serves as a clean versatile environment having low power consumption and high cost-performance and is suitable not only for processing the next generation new devices but also for cross-disciplinary fields, including medical/hygienic applications. The early CUSPs [10], [11], [12], which, being originally desk-top clean boxes or chambers to be connected up to form a whole system like LEGO blocks, were not designed to have people inside. For effectively providing a space which closes to a conventional clean room, the tent type clean unit system platform (T-CUSP) has been deployed, and is used for sleep analyses[13], [14]. The CUSP can provide an approximately isolated air-tight space with dust- and the microbe-free environment as good as US FED 209E class 10 or ISO14644-1 class 4 in tent-type CUSP. It could effectively avoid outside particles (e.g. PM 2.5 and 10) entering T-CUSP inside, and approve gas-exchange. Figure 1 shows air cleaning performance of the T-CUSP, which can achieve a very low air-dust level (around 10µg/m3) even without using the air cleaner. Using an air purifier can speed up this process in 5 min.

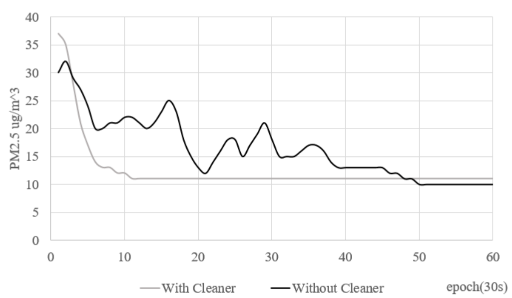

Figure 1. Comparison of the trend of PM2.5 reduction with or without air cleaner in the T-CUSP.

2.3 Sleep Environment and Monitoring

A T-CUSP sleep environment (200cm * 100cm * high 120cm) was built up as shown in Figure 2. Inside the tent, iAeris13 (SysinnoTechnology Inc, Taiwan) was used to monitor the air quality within the T-CUSP. It can provide real-time air quality information: PM2.5, PM10, CO_2 and other environment information (e.g. temperature and wet). The temperature was under controlled to 25~27-degree C by the air conditioner. An air cleaner (F-PXM55W, Panasonic Co, JP) was installed to pre-exclude the inside dust and the brought in by the subject. For more complete obtain the interaction between human sleep and environment, the monitor, air-condition and air-cleaner had been operation before subject enter the tent.

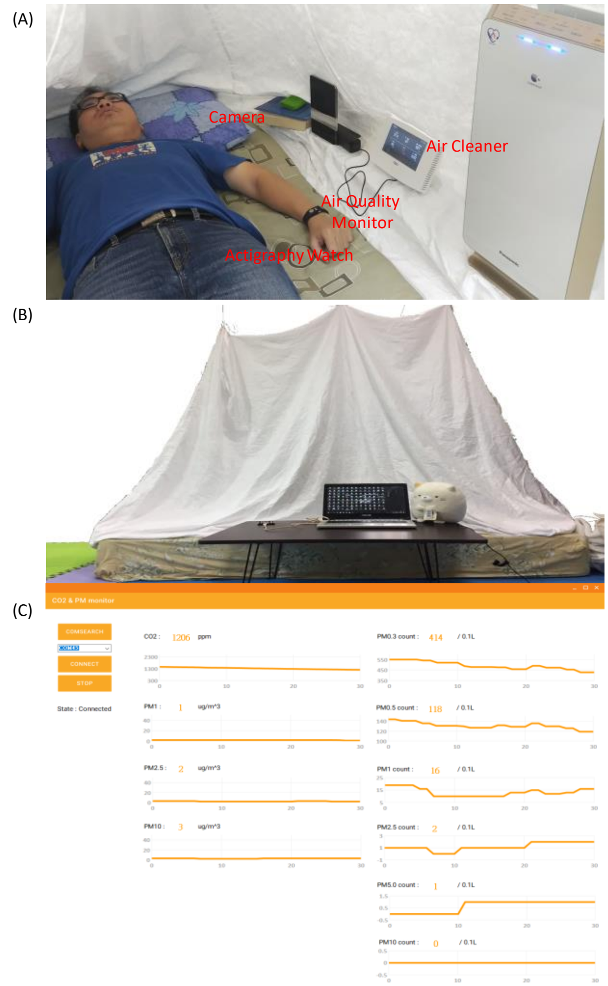

Figure 2. The setting of T-CUSP for all night sleep experiments. (A) Inside T-Cusp, iAeris13 was used to monitor the environment information: the concentration of particle and CO2, wet and temperature. (B)(C) Outside T-Cusp, We have developed a monitoring interface to observe time-course changes in various air indicators.

2.4 Sleep Signal Recording

In order to analyze the correlation between sleep patterns and the sleep environment in the T-CUSP, the PSG and actigraphy of subjects were simultaneously recorded. The PSG data including three bipolar physiological signals, an EEG channel (C3-A2, according to the international 10-20 standard system), an EOG channel (positioned 1 cm lateral to the left and right outer canthi) and a bipolar chin EMG channel were recorded through our developed mini PSG recording device [15]. The sampling rate was 250 Hz with 24-bit resolution. The 7 PSG sleep recordings were visually scored by a sleep expert using R&K and AASM rules for each 30-sec interval (called an epoch).

Moreover, the sleep behavior was monitored through a wearable watch-type actigraph recorder (AX3, Activity Ltd, UK) with 100 Hz sampling rate. The actigraph recordings were downsampled to 1Hz to estimate the sleep behavior (sleep/ wake) according to our proposed algorithm [16], [17].

2.5 Correlation Analysis between CO_2 and Actigraphy

Humans breathe CO_2 into the surrounding environment and it was the major source of CO_2 in T-CUSP. Hence, we proposed a flow for analyzing the correlation between CO_2 concentration and actigraphy during all night sleep (Figure 3). For each 30s epoch, if the measured CO_2 concentration increased over 20 ppm, the local maximum peak was detected and recorded. Then check the scoring of actigraphy if this epoch is awake or sleep. Each local maxima peak only counting once. An simple example of analyzing the correlation between CO_2 and actigraphy was shown in Figure 4. In this case, we observed six periods of CO_2 dioxide fluctuations which were synchronized with the wake stage of PSG and actigraphy scoring.

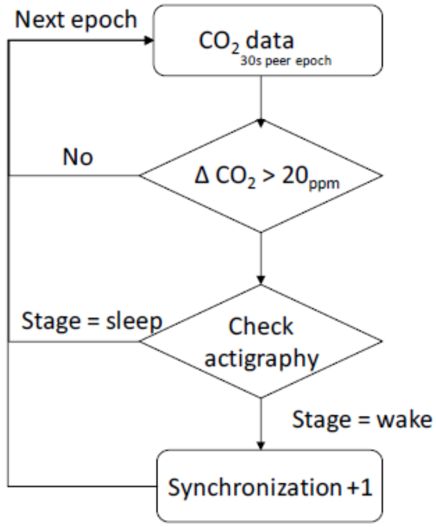

Figure 3. Flowchart of analyzing the correlation between CO2 and actigraphy.

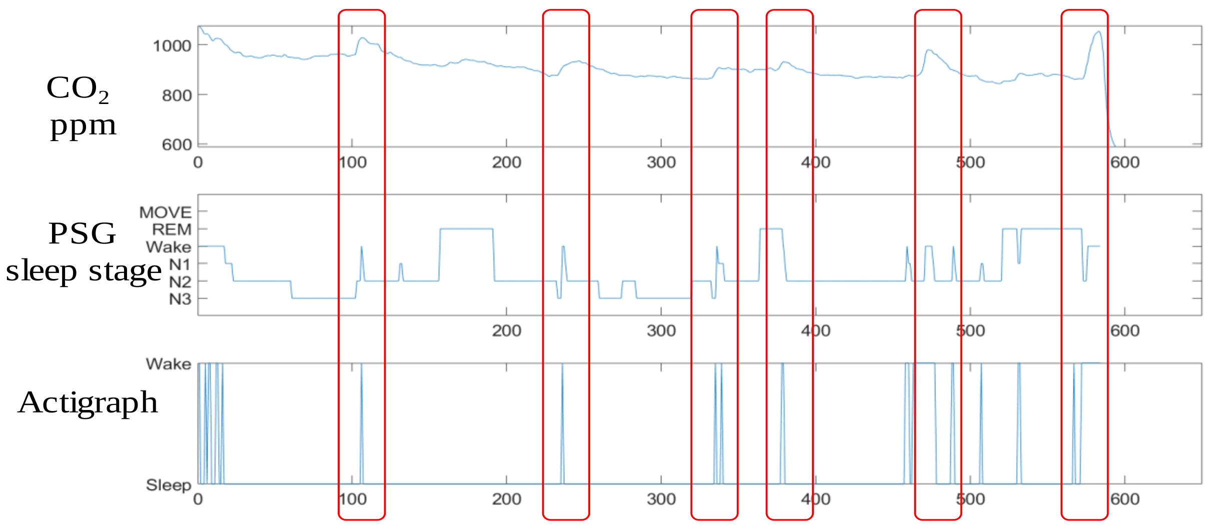

Figure 4. An example of analyzing the correlation between CO2 and actigraphy. The sudden rising in CO2 concentration could clearly reflect a wake stage with large body movements can be estimated by actigraphy (Subject 4).

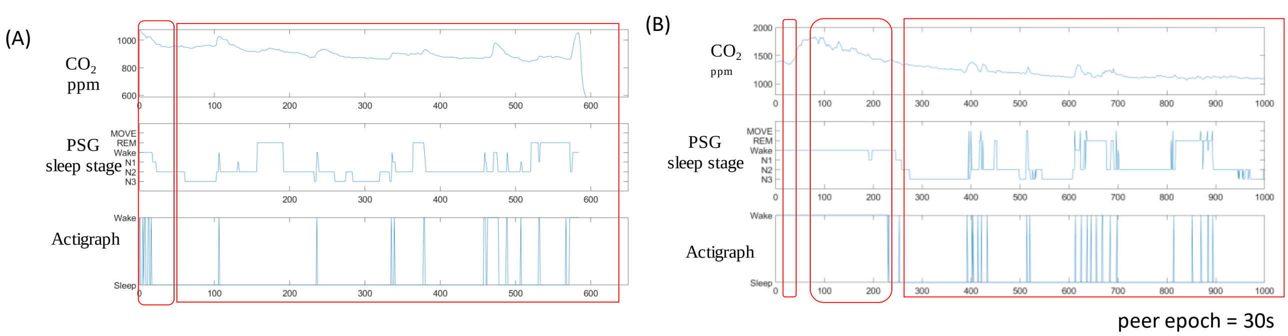

Figure 5. The observations of CO2 trends, sleep stage and sleep behavior(actigraphy). (A) shows the data from subject 4 with good sleep efficiency(SE: 94%). CO2 quickly drops below 1000 ppm and the sleep onset latency is only 7 min (Table 1). (B) shows the data from subject 6 with poor sleep efficiency (SE: 78%). After entering the tent, the subject took about 2Hrs to fall asleep and it made CO2 concentration stay at a high level.

3. RESULTS

3.1 Sleep Measures and Air Quality in T-CUSP

The T-CUSP provides a very convenient way of providing a highly air clean space for sleep. In this approximately closed sleeping space, the average sleep efficiency of the seven subjects was 83.48±6.72% and the average total sleep time was 328±73 minutes. During sleep stages (without large body movements), the average minimum values of PM2.5 & PM10 were 4.85±3.2 & 8.43±4.5 μg/m3, that are lower than the recommend quality (green / very well) in many countries (US green level: PM2.5<15 μg/m3 and PM10<54 μg/m3, UK and R.O.C: PM2.5<11.0 μg/m3 and PM10<16 μg/m3, Europe: PM2.5<15.0 μg/m3 and PM10<25 μg/m).

3.2 CO_2 and Sleep Stages

We analyzed the trend of CO_2 and compared it to the sleep stages. The trend can be separated into three phases. (1) Before subjects entered the T-CUSP, the CO_2 concentration is around 500~600 ppm. The entry of subjects would make CO_2 rise quickly (over 1000 ppm). (2) Before sleep onset, the subject kept activations (e.g. reading the book and using a smart phone), the CO_2 would be high. (3) After sleep onset, CO_2 was kept decreasing and can fall below 1000 ppm.

Table 1 shows the maximum and minimum values of CO_2 trends in 7 overnight periods of sleep. The highest concentration of CO_2 would obtain before sleep onset. For all subjects, CO_2 can be reduced to very low levels after sleep onset (the average of minimum could arrival 919 ppm, that is lower than the recommended concentration of people living), even the CO_2 concentrations are high before sleep onset. This result supports that T-CUSP does keep the air clean and also have good performance in gas-exchange (Figure 5).

3.3 CO_2 and Sleep Behavior

Although the trend of CO_2 concentration is decreasing from wake to periods after sleep onset during an all night sleep, we can observed some fluctuations and they may be correlated with various sleep behaviors. Fig. 5 (A) shows the data from subject 4 with good sleep efficiency(SE: 94%). CO_2 quickly drops below 1000 ppm and the sleep onset latency is only 7 min (Table 1). Fig. 5 (B) shows the data from subject 6 with poor sleep efficiency (SE: 78%). After entering the tent, the subject took about 2Hrs to fall asleep and it made CO_2 concentration stay at a high level. However, The CO_2 could fall below 1000ppm during the sleep phase for both subjects.We counted the epochs in which the CO_2 rising over 20 ppm and the results show that 91% of detected epochs were accompanied by significant body movements, and could be identified as wake stages.

4. DISCUSSION

In this paper, a tent-type clean unit system platform (T-CUSP) for sleep environment enhancement is constructed and a corresponding algorithm to estimate objective sleep measures by analyzing the fluctuation of air-borne particle counts is developed. The experimental results demonstrate the feasibility of constructing an air-clean environment with non-contact sleep assessment to support healthy sleep. Before sleep onset, subject's activity would increase the PM2.5 / 10 and CO2 to a relatively high level. However, during sleep, PM2.5 / 10 and CO2 will gradually decrease and satisfy human safety standards. In addition, we also proposed a simple flow for analyzing the correlation between air particle counter and sleep stage/behavior. Experimental results show that 91% of CO2 suddenly increasing (>20ppm) were related to large body movements, and can be used to identify sleep-awak states [15], [16].

Table 1 the maximum and minimum values of CO_2 trends in 7 overnight periods of sleep

ID	Sleep onset latency (min)	CO2 (ppm)					
		Before sleep onset			After sleep onset		
		Mean	Max	Min	Mean	Max	Min
1	70	1637	2248	1411	1309	1753	813
2	44	1625	1901	1345	1158	1617	999
3	7	1533	1631	1312	1005	1498	874
4	8	1034	1077	1005	907	1030	843
5	26	1509	1694	1395	1230	1696	1017
6	116	1575	1832	1348	1178	1524	958
7	59	1544	2254	1207	1067	1463	930
Mean		1494	1805	1289	1122	1512	919
STD		193	374	131	128	220	72

Currently, most sleep monitoring approaches require user to manually note the exact time in bed for sleep measure analysis. According to the observation of the CO2 trends, we found that the user entering the T-CUSP and preparing to sleep will cause CO2 concentration rising significantly from 500 to over 1000 ppm. It might be an useful feature to estimate the time to bed and sleep onset time. Further, we proposed a method for analyzing the correlation between CO2 and actigraphy. Most of the motion-related CO2 fluctuations can be observed.

Because there are still significant CO2 fluctuatios less than 20 ppm and they are not necessarily related to movements. The experiments and data will be increase to investigate these CO2 changes and the relations to different sleep stages and behaviors in the future. It is also expected that the proposed systems and methods can cooperate with clinical medicine to observe the response of SDB patients in T-CUSP and to investigate the feasibility of improving sleep quality of SDB patients by providing a affordable air clean sleep environment.

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6. REFERENCES

[1] M. M. Ohayon. 2002. Epidemiology of insomnia: what we know and what we still need to learn. *Sleep medicine reviews,* vol. 6, no. 2, pp. 97-111.

[2] M. W. Mahowald and C. H. Schenck. 2005. Insights from studying human sleep disorders. *Nature,* vol. 437, no. 7063, p. 1279.

[3] M. Kampa and E. Castanas. 2008. Human health effects of air pollution. *Environmental pollution,* vol. 151, no. 2, pp. 362-367.

[4] X. Hu *et al*. 2012. Bioaccessibility and health risk of arsenic and heavy metals (Cd, Co, Cr, Cu, Ni, Pb, Zn and Mn) in TSP and PM2. 5 in Nanjing China. *Atmospheric environment,* vol. 57, pp. 146-152.

[5] N. Fann, A. D. Lamson, S. C. Anenberg, K. Wesson, D. Risley, and B. J. Hubbell. 2012. Estimating the national public health burden associated with exposure to ambient PM2. 5 and ozone. *Risk.*

[6] W. H. Organization. 2005. WHO Air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide. *Global update,* vol. 2006.

[7] Y.-L. Shen, W.-T. Liu, K.-Y. Lee, H.-C. Chuang, H.-W. Chen, and K.-J. Chuang. 2018. Association of PM2. 5 with sleep-disordered breathing from a population-based study in Northern Taiwan urban areas. *Environmental Pollution,* vol. 233, pp. 109-113.

[8] C. L. Jackson, S. Redline, and K. M. Emmons. 2015. Sleep as a potential fundamental contributor to disparities in cardiovascular health. *Annual review of public health,* vol. 36, pp. 417-440.

[9] A. Zanobetti *et al*. 2010. Associations of PM10 with sleep and sleep-disordered breathing in adults from seven US urban areas. *American journal of respiratory and critical care medicine,* vol. 182, no. 6, pp. 819-825.

[10] M. D. Rahaman, H. Kaiju, N. Kawaguchi, and A. Ishibashi. 2008. Ultra-High Cleanliness of ISO Class Minus 1 Measured in Triply Connected Clean- Unit System Platform. *Japanese Journal of Applied Physics,* vol. 47, no. 7R, p. 5712.

[11] H. Kaiju, N. Kawaguchi, and A. Ishibashi. 2005. Study of very low airborne particle count in clean-unit system platform. *Review of scientific instruments,* vol. 76, no. 8, p. 085111.

[12] A. Ishibashi, H. Kaiju, Y. Yamagata, and N. Kawaguchi. 2005. Connected box-units-based compact highly clean environment for cross-disciplinary experiments platform. *Electronics Letters,* vol. 41, no. 13, pp. 735-736.

[13] M. Yasutake and A. Ishibashi. 2017. A unique non-contact method to assess sleep quality by detecting body movements via monitoring air-borne particles in an ultraclean space. in *SLEEP*, vol. 40: OXFORD UNIV PRESS INC JOURNALS DEPT, 2001 EVANS RD, CARY, NC 27513 USA, pp. A289-A289.

[14] M. Yasutake and A. Ishibashi. 2016. Application of Clean Unit System Platform (CUSP) for sleep diagnostics: evaluation of sleep quality by monitoring airborne particles in an ultraclean space. in *JOURNAL OF SLEEP RESEARCH*, vol. 25: WILEY-BLACKWELL 111 RIVER ST, HOBOKEN 07030-5774, NJ USA, pp. 254-254.

[15] D.-W. Chang et al. 2012. Design and implementation of a modularized polysomnography system. *IEEE Transactions on Instrumentation and Measurement,* vol. 61, no. 7, pp. 1933-1944.

[16] S.-F. Liang *et al.*2011. Development of an actigraph system for sleep-wake identification. in *2011 IEEE International Instrumentation and Measurement Technology Conference*, 2011: IEEE, pp. 1-6.

[17] C.-E. Kuo, Y.-C. Liu, D.-W. Chang, C.-P. Young, F.-Z. Shaw, and S.-F. Liang. 2016. Development and evaluation of a wearable device for sleep quality assessment. *IEEE Transactions on Biomedical Engineering,* vol. 64, no. 7, pp. 1547-1557.