

An Experimental Study on Optimal Illuminance Condition of Ambient Light for Accurate Noncontact Heart Rate Measurement

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Abstract

Original Research Article

The imaging photoplethysmography (iPPG) technology is regarded as a promising one that can measure the vital signs like heart rate using facial video data of patient recorded by usual webcam, which can be easily affected by the surrounding illumination variations. In this study, in order to decide the optimum illuminance of ambient light for accurate HR measurement, some interesting experiments are performed for the self-collected data. Four representative methods are used for HR measurement, and the illuminance of ambient light is divided into 10 intervals. The analysis of experimental results show that illuminance range of 350-450lx is optimum with the smallest error and the largest precision. It can be also seen that among four methods, SB-CWT(CbCr)+SSA has the best performance comparing with other methods. Moreover, experimental results implies that once the proper method and optimum illuminance condition are provided, HR can be measured at a significantly high accuracy without reference to the illumination supply mode.

Keywords: iPPG, heart rate, illuminance, non-contact estimation, non-invasive technology.

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1. INTRODUCTION

For curing several diseases such as heart disease, septic shock and hypertension, measuring vital signs (heart rate, heart rate variability, respiratory rate, blood pressure, blood oxygen saturation and so on) with high precision is a primary and fundamental task [1-4]. With the rapid development and brilliant success in the field of hardware and software technologies, modern special devices have been able to measure the vital signs with the precision of more than 99% in real-time. These devices use the certain sensors which are attached to the special parts of human bodies to collect the information of human health, so they are called as contact or invasive devices.

Although such these contact and invasive devices can measure and monitor the human vital signs correctly, there are some cases in which they are not suitable or cannot be used. For example, when the patient, who is far away from the hospital without any special measurement devices, falls in a critical situation, he or she cannot obtain the information of his or her vital signs in a short time for the emergency treatment. Also, it seems to be not suitable for the patients with some skin allergies

to adapt these contact devices because of some pain or inconvenience during the measurement [5].

The facts mentioned above motivated the researchers to develop fresh methods to measure the vital signs without attaching sensors, which resulted in a new technology called as non-contact and noninvasive technology. Various non-contact and non-invasive technologies, such as Doppler effect-based technology ([6], [7]), laser radar-based methods ([8]-[10]), capacitively coupled sensors-based technology ([11]), and imaging photoplethysmography (iPPG) technology ([12], [13]) have been developed over the last two decades. Among all these technologies, iPPG technology has been regarded as a promising one because of its several advantages. First, patients do not feel any inconvenience in their activities during the measurement of vital signs. Second, only ordinary camera or webcam is needed for measurement, which requires a relatively low cost [14].

iPPG refers to a non-contact and non-invasive technology that can measure and evaluate the vital signs employing the patient's skin-video data collected by camera without attaching sensors



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to the skin [15]. Measurement of vital signs by using iPPG is based on the signal processing of facial video data; heart's systole and diastole causes the fluctuations in the hemoglobin amount in the microvascular organizations of the skin dermis, which leads to the fine quasi-periodic variations in the luminance intensity of optical signals. During the sophisticated signal processing of the patient's skin video data, some unwanted noise artifacts may inevitably affect the accuracy of the result. Among several noise artifacts, illumination variation interference and ambient light condition are the most critical factors that can affect the measurement, because the video data are always collected under the certain light condition [1, 16].

Many studies have been conducted to solve this illumination noise artifact problem [17] the methods to cope with the illumination noise artifact problem can be classified into two categories. The first category involves the methods such as EEMD and BSS which directly removes the illumination noise artifact from the facial region of interest (ROI), while the second category uses the background ROI as a noise reference to reduce the illumination noise artifact. Although these methods can reduce the illumination noise artifact to a certain level, there are some drawbacks. The first category has some drawbacks relevant to the weaknesses of the methods to remove the illumination noise artifact. The methods of the first category base on EMD such as EEMD and CEEMDAN cannot thoroughly settle the mode mixing problem [18], thus these methods may not remove the noise artifacts smoothly in the case that the frequencies of noise artifacts are near to the frequency of heart rate. For the methods based on the linear BSS, the established assumptions depend on the measurement environment [19]. Even though the assumptions are true, there are still some problems that which component has to be chosen as the pulse signal from the separated components. In the second category, the conditions of illumination noise artifacts for facial and background ROIs may be different, which can negatively effect on the estimation of heart rate. Recently, there has been one study that is based on the combination of SSA (singular spectrum analysis) and the modified SB (sub-band) method to cope with the drawbacks of the previous methods, which is called SB-CWT(CbCr)+SSA [17]. It shows a good performance superior to other methods, which can measure HR robustly even in the environment that illumination rapidly changes.

Although several methods mentioned above can effectively cope with the illumination noise artifact, it seems that they don't completely solve the illumination noise artifact problem in HR estimation using iPPG. This means that despite of the benefits of these methods, in some cases, the accuracy of HR estimation can be reduced much more than usual due to several reasons including illumination noise artifact. As described before, iPPG technology uses the facial video data of the patients to measure HR, so it may be very important to select the proper

measurement method and optimum ambient light condition. The term "optimum ambient light condition" refers to the illuminance condition of the environment in which the best or the most accurate result for HR measurement is obtained. As far as we know, no studies have found out the relation between the illuminance of ambient light and the accuracy of HR estimation.

In this paper, in order to get the best accurate result of HR measurement, some experiments are conducted to determine the optimum ambient light condition and the results are analyzed. The experiments are conducted for four representative methods of HR measurement using self-collected data in a room with sufficient illumination condition. After that, based on the recorded experimental data, the relation between the accuracy of HR estimation and the illuminance of ambient light is analyzed and the optimum ambient light condition is determined. Also, in every situation, the results of four methods are compared to select the proper measurement method.

2. MATERIAL AND EXPERIMENT

2.1 Self-collected data

In the experiment of this paper, 12 subjects including 7 males and 5 females voluntarily participated and their ages ranged from 19 to 28 years. They were all Asian and healthy. All of them were given an explanation of the experimental tasks and they signed an informed consent form before participating in the experiment.

2.2 Experimental setup

The experimental environment was shown in Fig.1 to collect the facial video data of the participants. The experiment was conducted in a room with the size of 6.5m (length) * 6m (width) * 3.5m (height). The room had a big window that can sufficiently let in the sunlight in the daytime. In order to provide a dynamic electric illumination condition, a white LED lamp panel FZ-12V-GD8 (FengChuan Ltd., Shenzhen, China, 12V, 15W), a DC power supply (MPS-3303C) and a control unit were utilized. The control unit was to change the energy of the light intensity of the LED lamp. The video data were recorded with a frame rate of 30fps and a resolution of 640×480 by a webcam built in laptop (Intel(R) Core (TM) i5-6300HQ @ 2.30GHz (4CPUs), 16G RAM) with the operating system Windows 10(64bit). To measure the illuminance of ambient light, an illuminometer (ST-520, China) was employed. The distance between the webcam and the participant was set as 1 meter. On the other hand, the real heart rates of the participants were measured by employing an ECG sensor (AD232, Shenzhen, China) for analysis of the experiment.

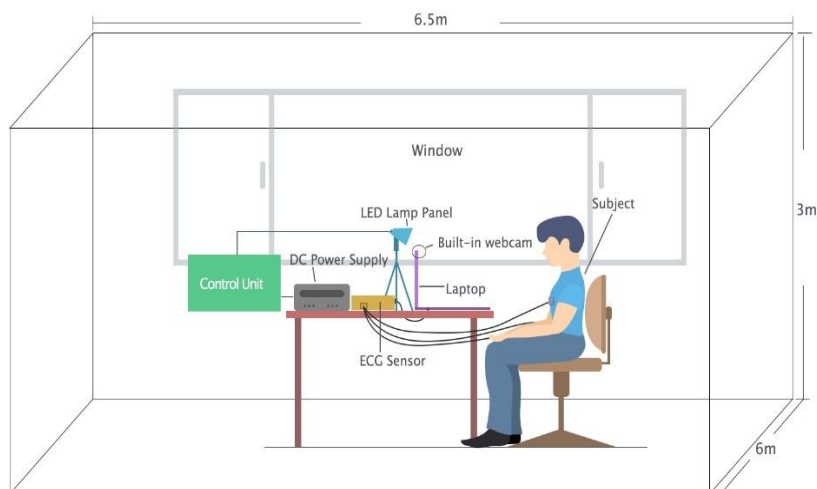


Fig.1 Experimental setup for video data collection

2.3 Methods

In this experiment, four representative methods introduced in [17] were used to measure HR remotely. They were IVA-EEMD, SB-CWT, SB-CWT (CbCr) and SB-CWT (CbCr) +SSA. The characteristics of four methods are as follows:

IVA-EEMD ([20]): This method estimates HR based on EEMD and it uses IVA to compare the signals from the facial ROI and background ROI for removing the illumination noise artifact from the facial iPPG signal, which is based on JBSS.

SB-CWT ([21]): It is one kind of sub-band method using continuous wavelet transform and it show a better performance than SB and POS methods.

SB-CWT (CbCr): This method modifies SB-CWT method by using CbCr-projection matrix U_{CbCr} instead of the POS-projection matrix U_{POS} employed in SB-SWT method.

SB-CWT (CbCr) +SSA [17]: It combines SB-CWT (CbCr) and SSA, which directly extracts the illumination variation from the facial ROI.

2.4 EXPERIMENTAL PROCEDURE

2.4.1 Selection of the optimum ambient light condition

The experiment was repeated for each participant and each method in the condition of changing natural light so that the optimum illuminance for HR measurement could be decided. During the measurement, participants sit on a chair

and maintained the static states without any movements. The illuminance was measured using a prepared illuminometer on the facial skin of the participant. HRs were measured for 10 illuminance intervals from 50lx to 1050lx with the length of 100lx. The reason for deciding the start point and end point of the illuminance range as 50lx and 1050lx was that the illuminances at the dawn when the participant's face could be distinguished and at the noon when the sun shone most brightly were 48lx and 1062lx respectively (in a shiny day). To sum up, for one participant, HR was measured 40 times. At the same time, real HRs were also measured by ECG sensors attached to the participant's body.

2.4.2 Comparison between the natural and electric light conditions

Based on the selection of the optimum illuminance interval for HR estimation, the experiment for comparing the accuracy of HR estimation between the natural and electrical light conditions was performed. To provide an electric light environment, the experiment was conducted at night when it was dark. Employing the control unit, the light intensity of the LED lamp panel was controlled up to the illuminance interval that was selected as the optimum. After that, for one method which showed a best performance, HR was estimated across 12 participants. Finally the results were compared and analyzed.

3. ANALYSIS RESULTS

To select the optimum illuminance of natural ambient light, five statistical metrics including mean error (ME), mean absolute error (MAE), root mean squared error (RMSE),

precision (P%) and Pearson correlation coefficient were employed [17]. For nth participant, the HR remotely measured by iPPG signals and the HR directly measured by ECG sensor

can be written as HR_n^{iPPG} and HR_n^{ECG} , respectively. The statistical metrics can be denoted as follows:

$$ME = \frac{1}{N} \sum_{n=1}^N (HR_n^{PPGI} - HR_n^{ECG}) \quad (1)$$

$$MAE = \frac{1}{N} \sum_{n=1}^N |HR_n^{iPPG} - HR_n^{ECG}| \quad (2)$$

$$RMSE = \sqrt{\frac{1}{N} \sum_{n=1}^N (HR_n^{iPPG} - HR_n^{ECG})^2} \quad (3)$$

$$P_{\%} = \frac{\#\{n \mid |HR_n^{iPPG} - HR_n^{ECG}| < AT\}}{N} \times 100\% \quad (4)$$

$$r = \frac{\sum_{n=1}^N (HR_n^{iPPG} - \overline{HR_n^{iPPG}})(HR_n^{ECG} - \overline{HR_n^{ECG}})}{\sqrt{\sum_{n=1}^N (HR_n^{iPPG} - \overline{HR_n^{iPPG}})^2} \sqrt{\sum_{n=1}^N (HR_n^{ECG} - \overline{HR_n^{ECG}})^2}} \quad (5)$$

Where N is a total number of participants, AT denotes the threshold of the absolute error between the real HR and the estimated HR, $\overline{HR_n^{iPPG}}$ and $\overline{HR_n^{ECG}}$ represents the mean values of the estimated and the real HRs, respectively and P% is how many percent of all participants can be measured accurately with the absolute error smaller than the threshold AT, i.e., the ratio of the number of correct estimations to the total number of estimations. In this analysis, AT was set as 5bpm. The Pearson correlation coefficient means the similarity or relation between two objects.

3.1 Analysis results for selection of the optimum ambient light condition

For four methods used in this experiment, the measured values of five statistic metrics are shown in Table 1. For convenience, let us index the illuminance intervals using numbers from 1 to 10. For example, interval 1 denotes to

illuminance from 50 to 150lx and interval 4 is from 350 to 450lx. The values of statistic metrics were calculated using the HRs of 12 participants measured by iPPG technology and ECG sensor. As can be seen in Table 1, in the case of IVA-EEMD, among 10 illuminance intervals, interval 3 showed the smallest MAE (5.71bpm), RMSE (9.28bpm) and the largest precision (68.3%), Pearson correlation coefficient (0.29). It means that HRs were measured most accurately in this interval. On the other hand, in the weak light intensity conditions including interval 1 and 2, the measurement accuracy was the worst with the largest MAEs and RMSEs, while in the relatively strong light intensity conditions, the accuracy was a bit improved.

For other three methods including SB-CWT, SB-CWT (CbCr) and SB-CWT (CbCr) +SSA, interval 4 showed the optimum performance with smallest MAE and RMSE. The MAEs were 3.98bpm, 1.11bpm and 1.18bpm respectively, while the RMSEs were 5.17bpm, 2.82bpm and 2.11bpm respectively.

Table 1. Measured values of statistic metrics for 10 illuminance intervals in the natural light

		1	2	3	4	5	6	7	8	9	10
IVA-EEMD	ME (bpm)	-7.50	6.30	3.38	-4.32	4.71	4.13	4.08	-5.83	-5.98	6.21
	MAE (bpm)	14.51	10.6	5.71	7.28	7.82	7.11	7.09	8.71	9.10	10.08
	RMSE (bpm)	20.1	19.8	9.28	11.91	12.13	11.08	10.98	15.22	16.17	15.13
	P%(%)	48.3	52.6	68.3	64.3	62.7	64.1	64.0	55.8	53.2	51.2

	r	0.16	0.18	0.29	0.25	0.24	0.25	0.25	0.20	0.19	0.18
SB-CWT	ME (bpm)	4.38	4.08	-2.81	-2.09	3.10	-2.58	3.71	3.37	3.61	3.18
	MAE (bpm)	7.27	6.91	4.12	3.98	4.91	4.41	5.92	5.09	6.11	5.21
	RMSE (bpm)	12.18	13.18	5.98	5.17	8.71	7.81	9.11	8.91	11.29	8.61
	P%(%)	68.7	69.1	73.8	78.2	71.9	75.1	70.9	71.1	71.3	72.1
	r	0.31	0.38	0.61	0.69	0.51	0.63	0.52	0.53	0.51	0.62
SB-CWT (CbCr)	ME (bpm)	1.28	-1.31	0.81	-0.28	-0.29	-0.61	0.84	-0.79	0.51	-0.95
	MAE (bpm)	2.18	2.31	1.82	1.11	1.31	1.72	1.89	1.91	1.68	2.18
	RMSE (bpm)	4.21	4.38	3.75	2.82	2.91	2.81	3.04	2.91	2.72	3.11
	P%(%)	80.1	81.7	83.7	87.1	86.8	84.1	83.8	81.2	83.1	85.8
	r	0.78	0.77	0.79	0.84	0.83	0.80	0.79	0.78	0.80	0.86
SB-CWT (CbCr) +SSA	ME (bpm)	0.71	-0.63	-0.68	0.18	0.32	-0.21	-0.31	-0.29	0.39	0.35
	MAE (bpm)	1.81	1.58	1.71	0.91	1.18	1.23	1.20	1.33	1.41	1.38
	RMSE (bpm)	2.62	2.16	2.38	2.11	2.35	2.27	2.33	2.51	2.41	2.31
	P%(%)	89.2	89.4	90.1	92.5	91.1	91.8	91.2	90.2	91.1	90.8
	r	0.81	0.83	0.85	0.91	0.86	0.88	0.87	0.83	0.85	0.84

It reveals that in the interval 4, the accuracy was the highest for three methods. Similar to the IVA-EEMD, in the case of the relatively dark light intensity, the accuracy of measurement was not as good as the bright light intensity conditions. Under the bright light intensity conditions, the accuracies were a little lower than the optimum interval, but they were still good, comparing with IVA-EEMD. Fig. 2, Fig. 3 and Fig. 4 intuitively shows the MAE, RMSE and Precision across 10 illuminance intervals for four methods. As can be shown in these figures, in the interval 4, the MAEs and RMSEs were the smallest, while Precision was the largest, except for IVA-EEMD method, in which interval 3 had the best performance.

Comparing the performances of four methods, it can be clearly seen that SB-CWT (CbCr) +SSA has the best performance with smallest MAEs and the largest Precisions for various illuminances of ambient light. Especially, in the interval 4, the MAE and RMSE were 0.91bpm and 2.11bpm respectively, which were the smallest values. This seems to support the result of [17], in which it was proved that SB-CWT (CbCr) +SSA was an efficient method robust to interference of illumination variation.

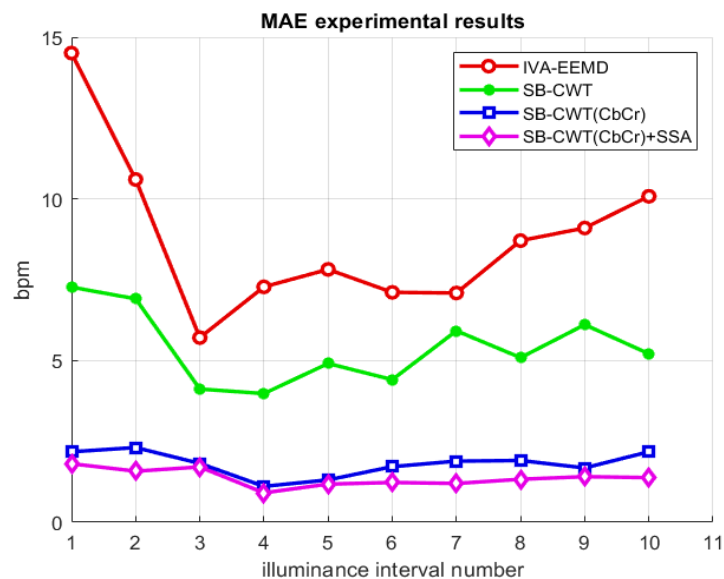


Fig. 2. MAE values in several illuminance intervals for four representative methods

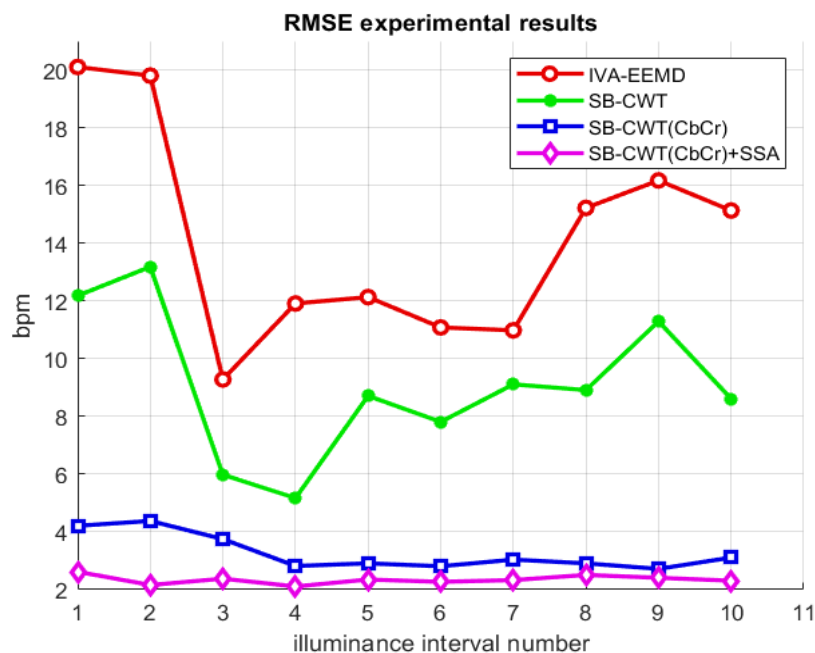


Fig. 3. RMSE values in several illuminance intervals for four representative methods

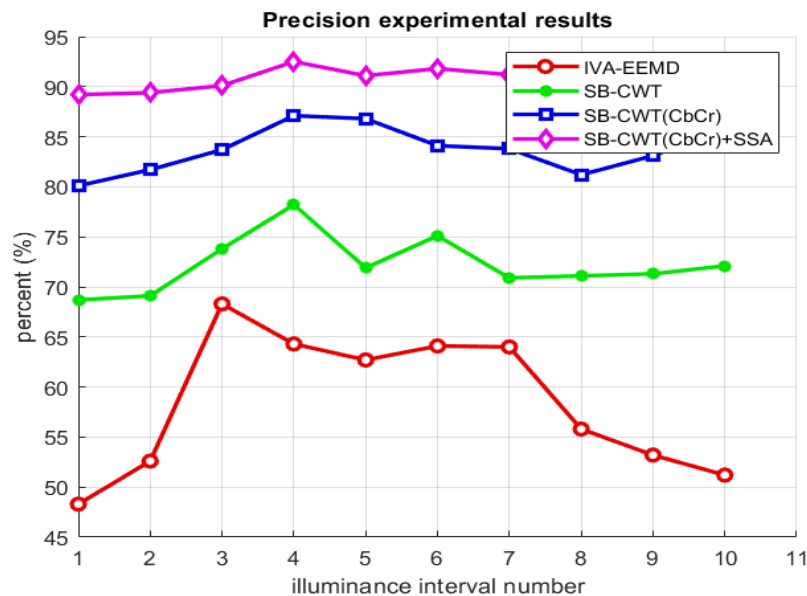


Fig. 4. Precision values in several illuminance intervals for four representative methods

To sum up, the optimum illuminance of ambient light for measuring HR by iPPG technology can be considered as interval of 350-450lx, and SB-CWT (CbCr) +SSA showed a best performance. In fact, besides the first two intervals of 50-250lx, we could hardly find difference in the values of several statistical metrics, which means that once proper method and illuminance of ambient light are provided, the accuracy of measurement can be maintained as a certain tolerant level. To get a more accurate measurement result, the optimum illuminance condition of 350-450lx must be satisfied.

3.2 Analysis results for comparison between natural and electric light conditions.

Based on the analysis results for optimum illuminance of ambient light, for two illuminance intervals of 250-350lx and 350-450lx, the experiment was conducted by using SB-CWT(CbCr)+SSA which showed a best performance, as described in 2.4.2. The results are listed in Table 2.

Table 2. Measured values of statistic metrics for optimum illuminance intervals in the natural and electric light conditions

		Natural light		Electric light	
		250-350lx	350-450lx	250-350lx	350-450lx
SB-CWT (CbCr)+SSA	ME (bpm)	-0.68	0.18	0.59	-0.21
	MAE (bpm)	1.71	0.91	1.32	1.01
	RMSE (bpm)	2.38	2.11	2.09	1.99
	P%(%)	90.1	92.5	90.6	92.1
	r	0.85	0.91	0.86	0.90

Comparing the numerical values between the natural and electric light conditions, it can be seen that the accuracies for two light conditions are about the same. For example, the values of MAEs and RMSEs for natural and electric light conditions in the illuminance of 250-350lx were 1.71bpm and 1.32bpm, 2.38bpm and 2.09bpm respectively, which implies that regardless of whether natural light condition or electric light condition, once the optimum illuminance condition and the proper method are satisfied, HR can be measured as approximately same as the real values.

4. DISCUSSION

In this part, some significant problems are discussed, based on the analysis results of experiments mentioned in the previous section. Also, the research goal and direction of the future are described.

In this study, some experiments were performed for two major purposes. The first one was to find out the optimum illuminance condition of ambient light for accurate measurement of HR using iPPG technology. As shown in Table 1, Fig. 2, Fig. 3 and

Fig. 4, in the case of IVA-EEMD method, the statistical values indicate that illuminance of 250-350lx is optimum for the HR measurement accuracy. In this illuminance interval, MAE and RMSE are 5.71bpm and 9.28bpm, respectively, which are the smallest, while Precision is 68.3%, which is the largest, comparing with other intervals. Although this illuminance condition shows the most accurate results, the error is considerably high, compared with the real values, which means that IVA-EEMD method is not stable for illumination variation. On the other hand, for remaining 3 methods including SB-CWT, SB-CWT(CbCr) and SB-CWT(CbCr)+SSA, the illuminance of 350-450lx is selected as optimum for HR measurement accuracy, of which SB-CWT(CbCr)+SSA is regarded as the best with smallest error and largest precision. For SB-CWT(CbCr)+SSA method, MAE, RMSE, Precision and Pearson correlation coefficient are 0.91bpm, 2.11bpm, 92.5% and 0.91, respectively, which points out that the results are almost same as the real HR values. The illuminance of 350-450lx was measured on the facial skin of participant in a room with big window facing southeast direction, at the time from 8.30 to 9.20 A.M in a shiny day of September. In addition, it can be found that in the condition of being provided the bright illuminance, the accuracy is changed within a small range, which means that unless the ambient light was considerably dark, a relatively high accuracy can be obtained in HR measurement by iPPG technology.

The second purpose was to confirm which condition was better among natural and electric light conditions for accurate measurement of HR using iPPG technology. At night, or in the room without window, there is no sunshine, so electric illumination is needed to measure HR by iPPG technology. But nobody knows if the accuracy of HR measurement is better under the condition of electric illumination than under the condition of natural light or not. As can be seen in Table 2, there is little difference between the values under the conditions of natural and electric illuminations. For the case of illuminance of 350-450lx, MAE and RMSE are 0.91bpm and 2.11bpm respectively under the natural illumination condition, while they are 1.01bpm and 1.99bpm respectively under the electric illumination condition. These numerical values imply that once the optimum illuminance condition is satisfied, HR can be measured at a relatively high accuracy irrespective of illumination supply mode. From the discussion above, it seems that in the hospitals or other health care facilities, it may be necessary to establish an optimum illuminance environment to measure HR more accurately for unusual or special patients like with strong skin allergies.

In this study, experiments were conducted for the participants who sit on the chair without any motion, so the effect of motion artifact noise on the accuracy of HR estimation was not considered. This suggests that experiments even considering the motion noise artifacts might be needed to decide the optimum HR measurement condition in future works.

5. CONCLUSION

In this study, some interesting experiments are performed to decide the optimum illuminance condition of ambient light for accurate HR measurement by iPPG technology. Four representative methods are used to remotely measure HR, and 10 illuminance intervals are set and 12 volunteers take part in the experiments. The analysis of experimental results shows that the illuminance of 350-450lx is optimum for HR measurement for most of methods. Under the relatively bright illuminance conditions (more than the optimum illuminance), the accuracy of HR measurement is hardly changed. Also, among four methods, SB-CWT (CbCr) +SSA shows the best performance, which supports the result of [17] that claims that it is robust to the interference of illumination variations. Furthermore, analysis results suggest that once the proper measurement method and optimum illuminance condition are provided, HR can be measured remotely at a considerably high accuracy irrespective of illumination supply mode. This experimental study might be helpful for HR measurement of unusual or special patients who cannot use normal sensors because of some reasons like strong skin allergies.

REFERENCES

- [1] X. Chen, J. Cheng, R. Song, Y. Liu, R. Ward, Z.J. Wang, Video-based heart ratemeasurement: Recent advances and future prospects, *IEEE Transactions on Instrumentation and Measurement* 68 (10) (2019) 3600–3615, doi:10.1109/TIM.2018.2879706.
- [2] X. Li, J. Chen, G. Zhao, M. Pietikäinen, Remote heart rate measurement from face videos under realistic situations, in: *2014 IEEE Conference on Computer Vision and Pattern Recognition*, 2014, pp. 4264–4271, doi:10.1109/CVPR.2014.543.
- [3] L. Iozzia, L. Cerina, L. Mainardi, Relationships between heart-rate variability and pulse-rate variability obtained from video-PPG signal using zca, *Physiological Measurement* 37 (11) (2016) 1934–1944, doi:10.1088/0967-3334/37/11/1934.
- [4] X.R. Zhang, Q. Ding, Respiratory rate estimation from the photoplethysmogram via joint sparse signal reconstruction and spectra fusion, *Biomedical Signal Processing and Control* 35 (11) (2017) 1–7, doi:10.1016/j.bspc.2017.02.003.
- [5] J.S. Ryu, S.C. Hong, S. Liang, S.I. Pak, L. Zhang, S. Wang, Y. Lian, A real-time heart rate estimation framework based on a facial video while wearing a mask, *Technology and Health Care* 31 (2023) 887-900, doi: 10.3233/THC-220322
- [6] M. Mercuri, Y.H. Liu, I. Lorato, T. Torfs, A. Bourdoux, and C. Van hoof, "Frequency-tracking C W doppler radar solving small-angle approximation and null point issues in non-contact vital signs monitoring," *IEEE Trans. Biomed. Circuits Syst.*, vol. 11, no. 3, pp. 671–680, Jun. 2017.

- [7] A. Al-Naji, A.G. Perera, and J. Chahl, "Remote monitoring of cardiorespiratory signals from a hovering unmanned aerial vehicle," *Biomed. Eng. Online*, vol. 16, no. 1, p. 101, 2017. [Online]. Available: <https://biomedical-engineering-online.biomedcentral.com/articles/10.1186/s12938-017-0395-y>
- [8] A.D. Kaplan, J.A. O'Sullivan, E.J. Sirevaag, P.H. Lai, and J.W. Rohrbaugh, "Hidden state models for noncontact measurements of the carotid pulse using a laser doppler vibrometer," *IEEE Trans. Biomed. Eng.*, vol. 59, no. 3, pp. 744–753, Mar. 2012.
- [9] W. Hu, Z. Zhao, Y. Wang, H. Zhang, and F. Lin, "Noncontact accurate measurement of cardiopulmonary activity using a compact quadrature Doppler radar sensor," *IEEE Trans. Biomed. Eng.*, vol. 61, no. 3, pp. 725–735, Mar. 2014.
- [10] A. Al-Naji, G. Kim, and C. Javaan, "Monitoring of cardiorespiratory signal: Principles of remote measurements and review of methods," *IEEE Access*, vol. 5, pp. 15776–15790, 2017.
- [11] A.E. Mahdi and L. Faggion, "Non-contact biopotential sensor for remote human detection," *J. Phys. C onf. S er.*, vol. 307, 2011, Art. no. 012056.
- [12] S. L. Bennett, R. Goubran, and F. Knoefel, "Examining the effect of noise on biosignal estimates extracted through spatio-temporal video processing," in *Proc. 41st Annu. Int. Conf. IEEE EMBC*, 2019, pp. 504–4508.
- [13] Q. Fan and K. Li, "Non-contact remote estimation of cardiovascular parameters," *Biomed. Signal Process. Control*, vol. 40, pp. 192–203, 2018.
- [14] J.S. Ryu, S.C. Hong, S. Liang, S.I. Pak, Q. Chen, S. Yan, Research on the combination of color channels in heart rate measurement based on photoplethysmography imaging, *Journal of Biomedical Optics*, Vol. 26(2), pp 134-145, 2021
- [15] T. Wu, V. Blazek, H.J. Schmitt, Photoplethysmography imaging: a new noninvasive and noncontact method for mapping of the dermal perfusion changes, *Optical Techniques and Instrumentation for the Measurement of Blood Composition, Structure, and Dynamics*, Proceedings of SPIE (2000) 4163, doi:10.1117/12.407646.
- [16] A. Al-Naji, A.G. Perera, J. Chahl, Remote measurement of cardiopulmonary signal using an unmanned aerial vehicle, *IOP Conference Series: Materials Science and Engineering* 405 (2018) 012001, doi:10.1088/1757-899X/405/1/012001.
- [17] Ryu J, Hong S, Liang S, Pak S, Chen Q, Yan S. A measurement of illumination variation-resistant noncontact heart rate based on the combination of singular spectrum analysis and sub-band method. *Comput. Meth. Programs Biomed.* 2021; 200(3): Art. No. 105824. doi: 10.1016/j.cmpb.2020.105824.
- [18] B. Tang, S. Dong, T. Song, Method for eliminating mode mixing of empirical mode decomposition based on the revised blind source separation, *Signal Processing* 92 (1) (2012) 248-258.
- [19] A. Lam, Y. Kuno, Robust Heart Rate Measurement from Video Using Select Random Patches, in: 2015 IEEE International Conference on Computer Vision (ICCV), Santiago, 2015, pp. 3640–3648, doi:10.1109/ICCV.2015.415.
- [20] J. Cheng, X. Chen, L. Xu, Z.J. Wang, Illumination variation-resistant video-based heart rate measurement using joint blind source separation and ensemble empirical mode decomposition, *IEEE Journal of Biomedical and Health Informatics* 21 (5) (2017) 1422–1433, doi:10.1109/JBHI.2016.2615472.
- [21] M. Finžgar, P. Podržaj, A wavelet-based decomposition method for a robust extraction of pulse rate signal from video recordings, *PeerJ* 6 (2018) 1–26, doi:10.7717/peerj.5859.