A Multi-wavelength Photoplethysmography System for Sleep Quality Monitoring

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***Abstract*— This study proposes an intraoral, wearable, and noninvasive consumer electronics system based on the measurement of photoplethysmography (PPG) signals from the oral cavity for monitoring sleep quality. The system consists of a dual-channel PPG sensor and a Bluetooth module integrated with the microprocessor. It is experimentally demonstrated that the PPG signals measured by the proposed intraoral wearable system have a relatively identical morphology, i.e., baseline, frequency, and detectable peaks, as those recorded by an FDA-approved home sleep test module, which places at the conventional anatomical site, i.e., the fingertip. Thanks to the high quality of the captured PPG signals, the apnea-hypopnea index (AHI) can be calculated as an indicator of sleep quality. A comparison between the AHI values estimated by the FDA-approved home test and our proposed sleep monitoring system confirms that our monitoring device and its implemented algorithm can accurately predict the AHI. Therefore, the proposed sleep monitoring system can be integrated with a common oral appliance to monitor the efficacy of oral appliance therapy on a regular basis.**

Keywords*— Photoplethysmography (PPG), multi-wavelength, sleep monitoring, wearable, apnea-hypopnea index (AHI)

I. Introduction

The quality of sleep has a major impact on the quality of life, while many endeavors have been made to monitor sleep, diagnose sleep disorders and apply appropriate treatments. According to statistical reports, 50-70 million adults in the U.S. have a sleep disorder [1]. A clinically accepted method of monitoring sleep is polysomnography (PSG), which continuously measures various signals, such as brain waves, eye movements, muscle activity, and cardio respiratory parameters, then a trained healthcare staff analyzes them and makes a recommendation. It is widely recognized that oral appliance therapy (OAT) is an appropriate method for the treatment of sleep apnea. On the other hand, since PSG requires a complicated clinical setting and the number of available sleep study laboratories is universally limited, the efficacy of OAT cannot be regularly monitored in the home or outpatient setting. In this context, there is a great need for alternative techniques to measure sleep quality outside the medical clinic through wearable devices.

To date, health monitoring has benefited greatly from the unique properties of optical technology. As such, optical sensors have found a wide range of applications, including both bulky clinical instruments and lightweight wearable devices. Indeed, one of the commercially available optical sensors commonly used for wearable devices is photoplethysmography (PPG) [2]. PPG-based measurement technology is a non-invasive sensing method with a broad spectrum of clinical uses and can provide important information on cardiorespiratory parameters, namely heart rate (HR), respiratory rate (RR), and level of blood oxygen saturation (SpO_2). PPG signals obtained from the index finger have been shown to be of adequate quality to accurately estimate various vital signs [3]. As a matter fact, the melanin content of the skin may have a significant impact on the accuracy of PPG-based estimated cardiac parameters. For example, the measured SpO_2 at low level varies by 10% in people with higher skin melanin level, i.e., darker skin, depending on the pulse oximeter used [4]. Moreover, examination of a larger group of subjects has shown that black patients are almost three times more likely to have occult hypoxemia (i.e., the actual oxygen saturation of the arterial blood is less than 88%, while a pulse oximetry indicates more than 92%) than white patients [5].

Therefore, we are motivated to propose a PPG-based sleep monitoring platform that can be integrated into an oral appliance to measure PPG signals from the oral cavity. In this regard, the measured PPG signals are not dependent on melanin level of skin, and can accurately identify the sleep quality, and effectiveness of the oral appliance. The accuracy of the predicted sleep parameters is accredited in comparison to an FDA-approved home sleep apnea test module that is relatively close to PSG, known commercially as NightOwl [6].

II. Material and Method

The functional block diagram of the intraoral sleep quality monitoring system and its integration into a custom-made oral appliance is shown in Fig. 1. As shown in this figure, the proposed monitoring system consists of three main sectors, (i) power management, (ii) sensing, and (iii) control. The power management unit is responsible for providing constant power to the entire system, and for charging the rechargeable battery when the system is not being worn. The sensing unit is a dual reflective PPG sensor with wavelengths of 660 nm and 880 nm. It is worth mentioning that our deployed PPG sensor includes an integrated analog-front-end circuit to drive LEDs and convert the reflected light from the skin, measured by a photodetector, into digital form. The control sector is an RF transceiver with an on-board microprocessor, which controls

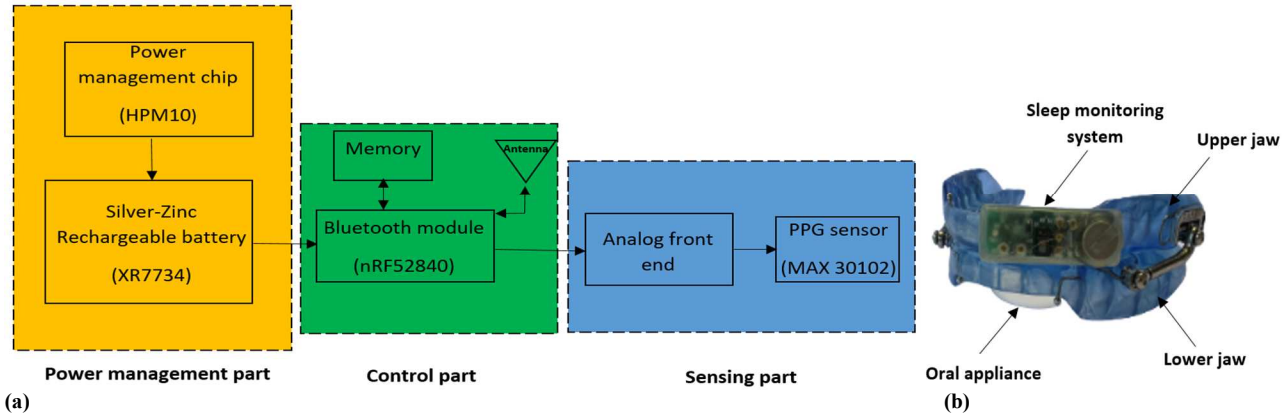

Fig. 1. (a) Block diagram of the proposed intraoral PPG-based sleep monitoring system, and (b) image of the monitoring system integrated into a custom-made oral appliance.

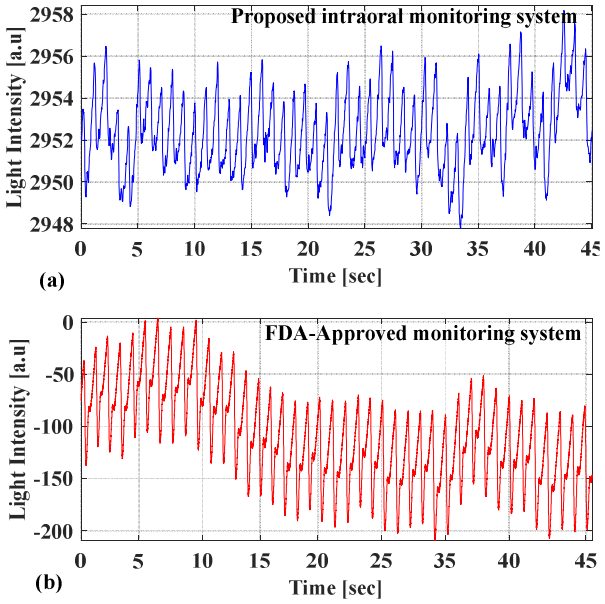

Fig. 2. Measured PPG signals at IR wavelength by (a) proposed intraoral sleep monitoring system and (b) FDA-approved device.

the PPG sensor and stores the data in a memory. The recorded PPG signals are then transferred via Bluetooth to a PC for processing.

Estimation of cardiorespiratory parameters were performed off-site without digital filtering. Further information on these techniques for estimating various cardiorespiratory parameters from the signals of a single PPG sensor can be found in our previous work [7]. In this study, a significant decrease, i.e., 3% of the SpO_2 for at least 10 seconds, is counted as an apnea event, and thus apnea-hypopnea index (AHI), as a metric of sleep quality is computed as follows:

$$AHI = \text{Number of more than 3\% drop for duration more than 3 seconds in } SpO_2 \text{ signal} \,/\, \text{Total sleep time.} \quad (1)$$

The required total sleep time in equation (1) can be determined from the change in heart rate. It is worth noting that the decrease in heart rate during sleep cycle is an indicator of the transition from wakefulness to sleep and, conversely, an increase in heart rate indicates the end of sleep time.

III. Experimental Results

The measured raw PPG data at the inferred wavelength from the oral cavity and the conventional anatomical site, i.e., the index finger, are shown in Fig. 2 (a) and (b), respectively. It is clear that the intraoral PPG signal measured from the oral cavity has the same morphology, such as detectable peaks, baseline and periodic changes, as the signal obtained from the finger. This confirms that PPG signals measured intraorally can be used for various cardiac parameters estimation, namely, HR and SpO_2.

The estimated HR value from our intraoral monitoring system and FDA-approved device for a duration of 60 minutes

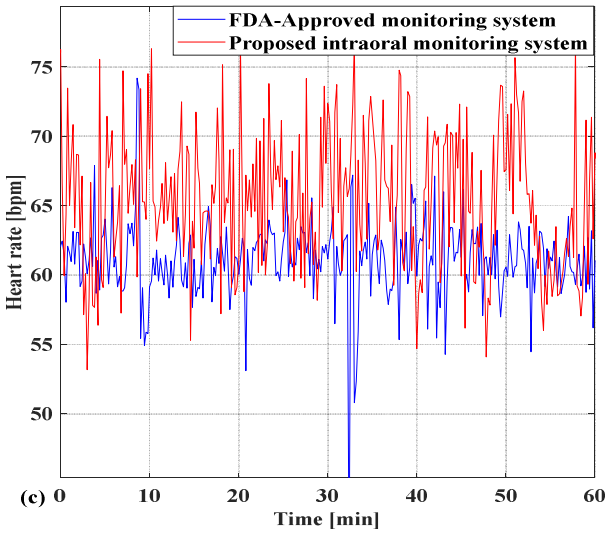

Fig. 3. Estimated HR values by the proposed intraoral sleep monitoring system and FDA-approved device.

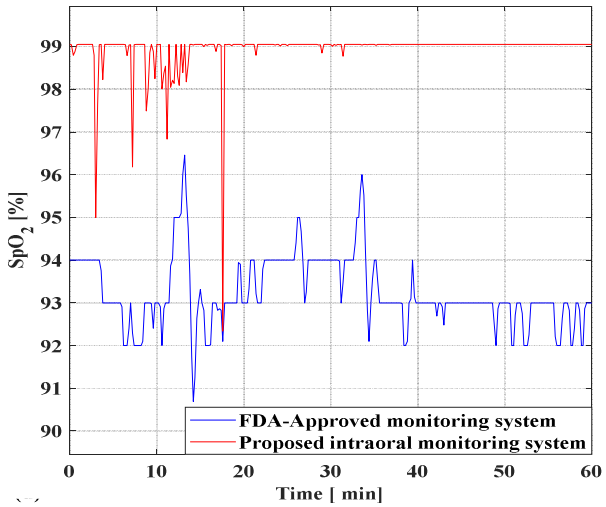

Fig. 4. Estimated blood oxygen saturation level, SpO_2, by the proposed intraoral monitoring system and FDA-approved device.

is illustrated in Fig. 3. HR value estimated from intraorally measured PPG signal exhibits a fairly similar behavior to the finger-measured HR, with an average variation of 5 beat per minute (bpm) over one hour of measurement, as shown in Fig. 3.

The estimated SpO_2 by PPG signals measured by our intraoral monitoring system and the commercially available FDA-approved device, shown in Fig. 4. This figure indicates that the estimated SpO_2 value from the oral cavity is higher than the one measured at the fingertip. This is mainly due to the different composition of peripheral skin at these two anatomical sites, i.e. mouth and fingertip. It should be noted that for monitoring sleep quality, the absolute value of cardiac parameters, e.g. SpO_2, is not necessary, while its changes (trend) over time are used in the algorithm of sleep quality monitoring. In this context, it is clear that the measured signals from the oral cavity and fingertip have an identical trend, which means that for both signals sudden changes can be observed at most at the same time.

According to the SpO_2 signals shown in Fig. 4 and equation (1), the AHI predicted by our proposed monitoring system is 2, whereas the FDA-approved AHI is estimated to be 1. Such a close correlation confirms the ability of our proposed intraoral monitoring system to effectively and efficiently monitor sleep quality.

IV. Conclusion

In this study, an intraoral wearable device that can be integrated with oral appliances is proposed. It is experimentally demonstrated that the proposed intraoral monitoring system is capable of measuring high-quality PPG signals from the oral cavity, while these measured signals can be used to estimate various cardiorespiratory parameters and ultimately to determine sleep quality. To monitor sleep quality, the apnea-hypopnea index (AHI) was predicted from the intraorally measured HR and SpO_2 signals. As a result, integration of the intraoral monitoring system with an oral device is a feasible method for determining the efficacy of OAT.

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