# Sleep Monitoring with intraorally measured Photoplethysmography (PPG) signals

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***Abstract*— According to statistical reports, the number of people suffering from a sleep disorder is increasing as the population ages, and untreated sleep disorders lead to serious illness. Unfortunately, the development of sleep disorders cannot be monitored regularly at present, even after diagnosis. This study proposes an intraoral PPG-based sleep monitoring system to measure PPG signals from the oral cavity and predict different sleep stages in addition to estimating apnea-hypopnea index (AHI). The proposed sleep monitoring system can be integrated into an oral appliance to be worn during sleep, thanks to its physical aspect and water resistance. The accuracy of the estimation of HR and SpO2 parameters is validated in comparison with two FDA-approved pulse oximeters placed at the conventional anatomic site, the finger. It is experimentally shown that the proposed intraoral sleep monitoring system, in conjunction with the applied algorithm, can estimate total sleep time, Rapid-eye movement (REM) time, and AHI with 92%, 75%, and 84% accuracy, respectively, compared with a home sleep apnea testing module.**

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

## I. INTRODUCTION

It is widely recognized that sleep has a significant impact on essential human parameters such as optimal health, well-being and the execution of daily activities [1]. Sleep is strongly correlated to the quality of life and affects physical and mental health, whereas untreated sleep disorders can lead to serious diseases. According to a recent report from the American Sleep Association (ASP), 50-70 million adults in the U.S. suffer from a sleep disorder [2]. This number is increasing every year, while it does not follow the increment of sleep laboratories, resulting in long waiting times. In the U.S., for example, waiting times for access to sleep laboratories range from a few weeks to more than a year, depending on geographic location [3]. Therefore, progression of sleep disorders, even after diagnosis, cannot be monitored regularly.

The gold standard for determining sleep quality is polysomnography (PSG), which measures various biological signals such as brain waves, eye movements, muscle activities, and cardio-respiratory parameters. Since PSG requires a complex clinical setting, alternative measurement methods have been proposed with the capability of conducting at home or in an outpatient setting in order to provide information on sleep quality. Actigraphy, which can be performed using a motion sensor, namely, accelerometer, is a relatively simple method for determining sleep echoes such as Wake After Sleep Onset and Total Sleep Time in addition to sleep postures [4][5]. Since the actigraphy method cannot provide information on cardiovascular parameters, its accuracy remains low. It is shown that the integration of the accelerometer with the electrocardiogram (ECG) and the use of recurrent neural networks with long-term memory leads to a classification of the different sleep stages with an average accuracy of 75.9% [6]. It is worth noting that the EEG (ectroencephalogram) signals measured from the scalp are highly applicable in assessing brain condition and diagnosing various sleep disorders [7]. As a matter of fact, each of these techniques (i.e., EEG and ECG) requires multiple contact electrodes to be placed at different anatomic locations, which minimizes the applicability of the monitoring device as a portable, convenient, and easy-to-use system. And, more importantly, none of these methods can estimate apnea-hypopnea index (AHI), which is an important metric for determining the severity of sleep disorders.

To mitigate the aforementioned obstacles, a group of cardiac parameters, i.e., heart rate (HR), respiratory rate (RR), and blood oxygen saturation (SpO2), can be readily obtained using a noninvasive measurement technique known as the photoplethysmogram (PPG) [8]. The PPG measurement method involves two light sources at two distinct wavelengths, usually red and infrared (IR), to transmit the light, and a photodetector to measure the reflected/transmitted light from/through the skin [9]. In the literature, the versatility of accurately measuring the cardio-respiratory parameters with PPG sensors is extensively discussed. It is also shown that PPG-based measurement data can be used for sleep stage monitoring. For instance, Korkalainen et al. [10] used data collected with simple finger pulse oximetry to train a deep-learning platform in order to classify sleep stages in people with obstructive sleep apnea (OSA). This developed sleep model is able to classify three different sleep stages, namely awake, non-rapid eye movement (NREM) and REM with an accuracy of 80.1% in comparison to the manual PSG-based sleep assessment method.

Indeed, the use of oral appliances, such as mandibular advancement devices (MADs), during sleep is an effective method for treating sleep disorders, i.e., OSA, and ultimately improving the quality of sleep [11]. However, unfortunately, the effectiveness of MAD therapy as an anatomic intervention to reduce pharyngeal collapsibility for each individual has not been measured at regular intervals. Therefore, in this study, 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. The accuracy of these intraoral

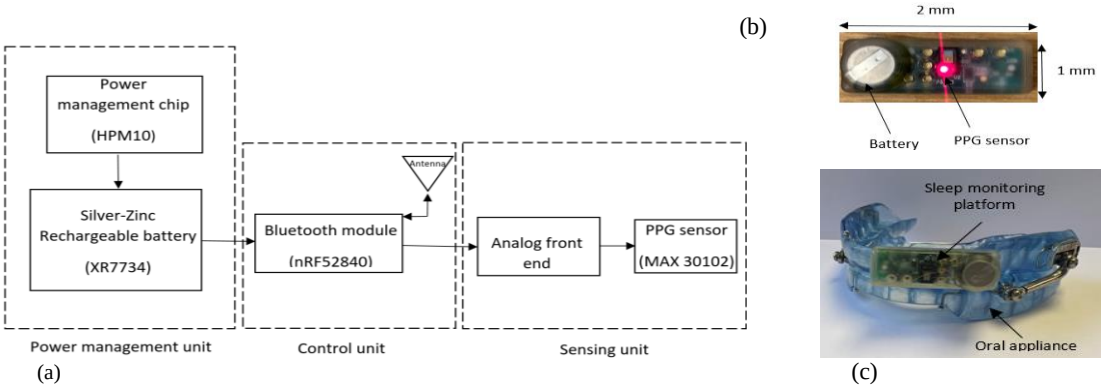


Fig. 1. (a) Functional block diagram of the proposed intraoral PPG-based sleep monitoring system. (b) Images of the implemented monitoring system, and (c) its integration with a custom made oral appliance.

estimated cardiorespiratory parameters is accredited in comparison to two FDA-approved medical pulse oximeters. Then, these estimated parameters are used to identify different sleep stages, i.e., wakefulness, NREM, and REM, in addition to calculate AHI.

## II. Hardware Implementation

The functional block diagram of the proposed intraoral PPG-based sleep stage monitoring system is shown in Fig. 1 (a). As shown in this figure, this monitoring system has 3 main functional units, namely, power management, sensing, and control. The power management system, which supplies power to the entire system, is a silver-zinc rechargeable battery with a peak amplitude of 1.8 V manufactured by Zpower. The capacity of this battery is 32 mAh, and a single charge can run the system for at least 7 hours. Furthermore, the power management unit includes a charging chip manufactured by Onsemito to charge the battery.

The sensing unit of the proposed sleep monitoring platform is a dual-channel PPG sensor with wavelengths of 660 nm and 880 nm manufactured by Maxim Integrated (model MAX30102). It is worth mentioning that the PPG sensor has the integrated front-end along circuitry including LED driving system, current analog to digital converter (ADC), data FIFO, and I2C interface. Consequently, the measured PPG signals at both wavelengths are digital and can be read via the digital pins of a microprocessor, i.e., SCL and SDA. The control unit that controls the overall functionality of the monitoring system is a RF transceiver with an integrated microprocessor manufactured by Nordic. Therefore, the digital outputs of the PPG sensor are captured by the control unit and stored in a 256M-bit serial flash memory manufactured by Winbon (model W25Q256JW).

When the monitoring system is placed on the ducking station for charging, the Bluetooth advertisement is triggered hence a nearby receiving station, such as a smartphone or PC, can retrieve the stored PPG signals in the memory. To protect the sleep monitoring system from the saliva, it is encapsulated with a biocompatible film that has 90% transmission at wavelengths of red and IR from Hapco Inc. (model Steralloy™-2463). Fig.1 (b) illustrates a prototype of intraoral PPG-based sleep monitoring platform. Integration of this monitoring platform with a custom-made oral appliance made by SomnoMed is shown in Fig. 1 (c).

## III. Calculation of Cardiorespiratory Parameters and Estimation of Sleep Stages

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 [5]

### A. *Sleep stages:*

In the literature, it is comprehensively discussed that HR can provide essential information about different sleep stages [12][13]. Therefore, in this study, REM and NREM phases are estimated based on the increase and decrease of HR, respectively. By studying a group of subjects over several nights, it was found that the transition from the wakefulness phase to the sleep phase resulted in a decrease in HR, while the transition from the sleep phase to the awake phase resulted in an increase in HR. Therefore, such a pattern observed at the beginning and end of the sleep period is used to estimate total sleep time.

### B. *Apnea-hypopnea index (AHI):*

AHI is the number of apneas (or hypopneas) recorded per hour during total sleep time. It is generally expressed as the number of events per hour. As known, t AHI can be used to classify the severity of OSA. In this study, a significant drop, i.e., 3% of SpO2 signal, is considered an apnea event, and AHI is estimated.

## IV. Results and Discussion

To determine the ability of the implemented PPG-based sleep monitoring to accurately measure intraoral PPG signals as well as assess the viability of the signal processing described in section III for estimating HR and SpO2 parameters, we compared the estimated HR and

SpO2 from the intraorally measured PPG signals with two stand-alone FDA-approved medical pulse oximeters from Wellue O2Ring and EMAY Sleep Oxygen Monitor, respectively. In this regard, a subject in the supine position wore the medical pulse oximeters on the left hand and the proposed sleep monitoring platform in the mouth. Moreover,

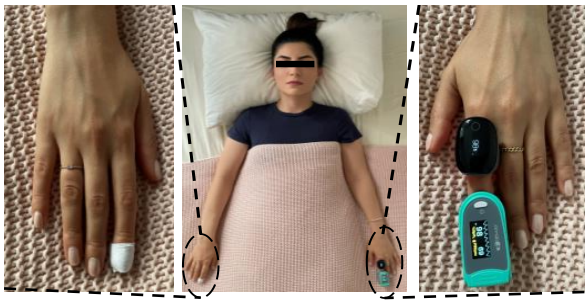

Fig. 2. Experimental setup utilized to validate HR, SpO2, AHI, and different sleep stages estimated by the intraoral sleep monitoring platform.

to validate the predicted sleep stages and AHI value, an FDA-approved home sleep apnea testing module known as NightOwl was worn on the right hand. NightOwl is an FDA-approved medical device that is clinically validated and has compliance with the PSG [14]. This experimental setup is shown in Fig. 2.

Fig. 3 shows the estimated HR and SpO2 parameters from our PPG-based sleep monitoring platform and those obtained from the FDA-approved pulse oximeters for a duration of 40 minutes. The PPG signals measured intraorally and our applied algorithm are able to estimate HR and SpO2 with an average deviation of 2 bmp and 3%, respectively, in comparison to data obtained from the commercial pulse oximeters placed at the conventional anatomical location, i.e., the finger. It can also be seen that the physiological signals measured with the intraoral sleep monitoring platform follow an identical pattern to their counterparts, while such agreement is observed for both HR and SpO2 signals.

The measured HR by the intraoral PPG-based sleep monitoring platform over one night is shown in Fig. 4 (a). As

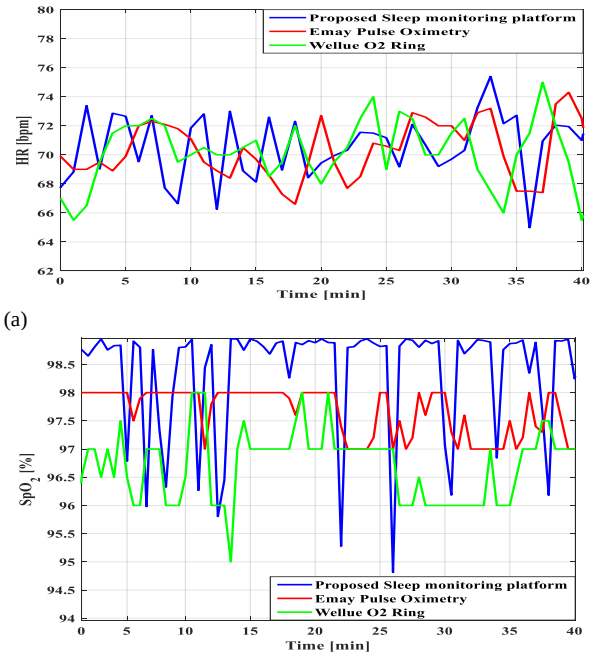


Fig. 3. Measured (a) HR and (b) $SpO_2$ by the intraoral PPG-based sleep monitoring platform, and medical grade FDA-approved pulse oximeters.

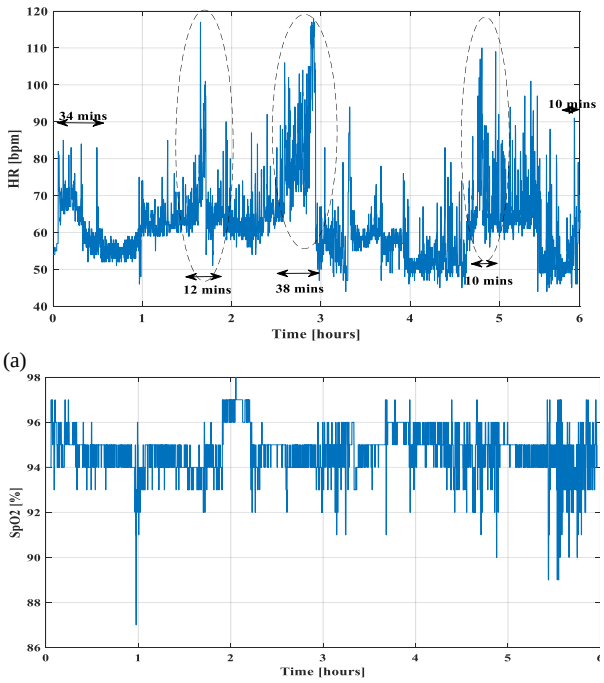


Fig. 4. Measured (a) HR and (b) $SpO_2$ by the intraoral PPG-based sleep monitoring platform during night.

can be seen, the HR value is not constant, while varying between 55 and 115 bpm corresponding to the different sleep stages. As mentioned in Section III, the HR value is high at the beginning of the sleep time, i.e., 80 bpm, while it decreases to 55 bpm after 34 minutes. This is an indicator that the subject is transitioning from the wakefulness state to the sleeping one. It can also be seen that the HR increases significantly again over time, which can be considered as a transition from the NREM state to the REM phase. At the end of the sleep period, the HR value increases again, indicating that the subject's wakefulness stage has begun. Consequently, the total sleep time is 5 hours and 36 minutes including 60 and 276 minutes REM and NREM, respectively.

Fig. 4 (b) shows the SpO2 value measured by the intraoral sleep monitoring platform. According to this figure, the mean SpO2 value during the measurement is 95.5%, dropping more than 3% (92.8%) 56 times. Therefore AHI value can be estimated to be 10. On the other hand, the home sleep apnea testing module, NightOwl, indicated a total sleep time of 5 hours and 10 minutes, 45 minutes of REM time, and an AHI of 12.

## V. Conclusion

In this study, an intraoral PPG-based sleep monitoring platform was proposed. The intraorally estimated HR and SpO2 parameters were used to determine different sleep stages and calculate AHI value. The experimental results indicated that our intraoral sleep monitoring system, can estimate total sleep time, REM time, and AHI with 92%, 75%, and 84% accuracy, respectively, compared with a home sleep apnea testing module.

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