Intraoral Monitoring of Photoplethysmogram Signal to Estimate Cardiorespiratory Parameters

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Abstract. Photoplethysmograpghy (PPG) is a simple, non-invasive, optical method already known in clinical and home monitoring setups for its wide applications in cardiorespiratory measurements such as heart rate, breathing, and blood oxygen saturation (SpO_2). Here, we present an intraoral measurement of such cardiorespiratory parameters using a photoplethysmogram (PPG) sensor. A reflective PPG sensor is placed inside the oral cavity, facing the buccal mucosa opposite to upper jaw, and PPG signal is obtained. The average heart rate, breathing signal and average SpO_2 variation are calculated from the intraoral PPG signal. Accuracy of the measured parameters are validated against standard monitoring methods: a commercial PPG sensor mounted on the left index fingertip to monitor heart rate and SpO_2 levels and a respiration monitoring belt worn around the diaphragm for breathing. Results obtained from subject's tests show an average absolute error of 0.75% in heart rate measurement and 5.83% in breathing detection compared to standard references. Whereas, the average variation in SpO_2 levels are 2.41% and 1.35% from the intra-oral measurement and the reference measurement, respectively. Intraoral measurement of such cardiorespiratory parameters can have useful applications such as smart mandibular advancement devices to monitor sleep while treating patients with sleep apnea.

Keywords: Photoplethysmography · Photoplethysmogram sensor · Intraoral monitoring · Heart Rate · Blood oxygen saturation · Breathing · Sleep Apnea

1 Introduction

Obstructive Sleep Apnea (OSA) is a health condition where patients suffer from multiple episodes of decreased or cessation of breathing events while sleeping [1]. If not treated, OSA may contribute to several medical conditions like Alzheimer's disease [2], cognitive issues, day-time sleepiness, hypertension, high blood pressure, cardiovascular diseases and may have an impact on the quality of our day-to-day life [3]. To diagnose OSA, a sleep study is required. Sleep studies include overnight monitoring of physiological parameters such as heart rate, SpO_2 saturation, breathing, EEG and EMG to detect

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restless leg syndrome. Intraoral mandibular advancement devices (MADs) provide safe and effective treatments of OSA [4]. Due to limited number of sleep labs across the world, sleep studies are not typically performed after the initiation of MAD treatment [5]. While sleep studies are typically done as a preliminary diagnostic step, data collected from an intraoral MAD could provide long-term monitoring of patients and their condition.

Developing a smart MAD, with an integrated sensing platform to monitor physiological parameters intraorally, would monitor both the state of the patient and the effectiveness of the treatment. To date, compliance monitoring during MAD treatment has been limited to rudimentary thermal recording [6]. There is a lack of research in intraoral monitoring of physiological parameters. One research group designed a pacifier with a reflective photoplethysmogram (PPG) sensor for acquiring oxygen saturation (SpO_2) intraorally, mainly for infants and critically burned subjects [7]. A possible study of acquiring some of those above mentioned health parameters intraorally will definitely provide a boon to the smart MAD technologies.

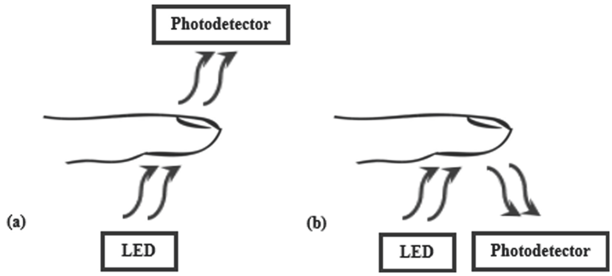

Fig. 1. Sensor placement configurations in photoplethysmography (PPG) with light source (LED) and photodetector: (a) transmissive PPG and (b) reflective PPG.

Photoplethysmography (PPG), a non-invasive method, is well known for its simplicity and widely used for monitoring cardiac parameters such as heart rate and blood oxygen saturation (SpO2) levels [8, 9]. It has also been employed as an indirect method for reliable monitoring of respiratory activity [10, 11]. In this method, a PPG sensor is placed on a skin surface such as fingertip, earlobe etc. to monitor the changes during blood flow [8]. This optical method uses a light source, see Fig. 1, to illuminate the sensor-skin contact area and the transmitted or reflected light is acquired using a photodetector from the opposite or same side of the light source. The former and the latter configurations are known as transmissive and reflective photoplethymsography, respectively.

In this study, we have investigated few intraoral locations for acquiring the PPG signal using a reflective PPG sensor. A good PPG signal is observed when the PPG sensor is placed inside the oral cavity in such a way so that it faces the buccal mucosa opposite to upper jaw. The acquired PPG signal is then processed to extract cardiorespiratory parameters like heart rate (HR), SpO_2, and breathing signal. The extracted heart rate and SpO2 from the intraoral PPG signal are validated against another reference PPG signal taken from the subject's left index finger. The breathing signal extracted from the intraoral PPG signal is compared with the breathing events recorded using a respiration monitoring belt worn around the subject's diaphragm. Results show potential for monitoring cardiorespiratory parameters intraorally and suggest that longitudinal sleep studies could be conducted for patients with sleep apnea by integrating a reflective PPG sensor into a MAD.

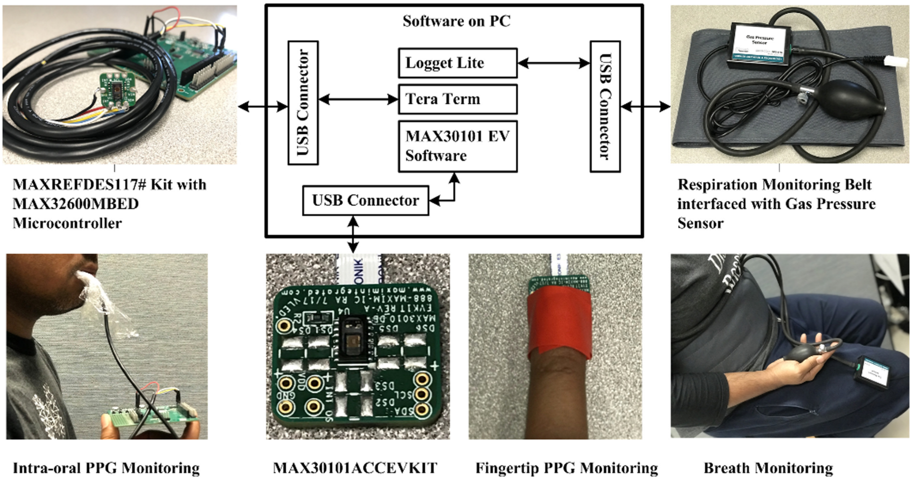

Fig. 2. Complete experimental setup of the sensors: MAXREFDES117# sensor kit for intra-oral PPG signal monitoring (left), MAX30101ACCEVKIT sensor kit for fingertip PPG signal monitoring (middle), and respiration monitoring belt with gas pressure sensor for breath monitoring (right); all are connected to a PC

2 Sensors and Experimental Setup

The complete experimental setup is shown in Fig. 2. To monitoring PPG signals intraorally, we used the sensor kit MAXREFDES117# containing MAX30102 reflective PPG sensor by Maxim integrated [12, 13]. This dual wavelength (Red and Infra-red) PPG sensor, designed for wearables, is compact in size and can be easily configured and programmed in any microcontroller with I^2C ports. To validate our calculated heart rate and SpO_2, another reference signal is recorded using a PPG sensor kit MAX30101ACCEVKIT [14], mounted on the fingertip of the index finger of the test subject's left hand. To validate breathing signal extracted from the intraoral PPG, another reference breathing signal is obtained using a respiration monitoring belt interfaced with a gas pressure sensor, by Vernier [15, 16]. The belt is generally worn around the diaphragm to monitor breathing. It is worth pointing out that the subjects were in complete resting position when the intraoral PPG and other reference signals are recorded and no artifacts (being motion, coughing etc.) were introduced during PPG and breathing monitoring. The objecting of this study is to acquire a good PPG signal intraorally and see if parameters heart rate, SpO_2, and breathing can be extracted from that location.

The intraoral PPG data are compared to fingertip PPG data, both recorded in 100 samples per second. A serial communication freeware 'Tera Term' was used to record the digitized intraoral PPG data on a personal computer (PC). The sensor kit MAX30101ACCEVKIT comes with a specific controller board, and a software. The software was used to log the data from the fingertip PPG signal to a PC. The breathing data was also sampled at 100 Hz and recorded on a PC with software provided with the respiration monitoring belt. Since all the sensors were being run simultaneously through different software, an 'autoit script' was written to start all the software almost at the same time for simultaneous data monitoring. Once the data are recorded, they are analyzed for cardiorespiratory parameters, given in the next section.

3 Estimation of Cardiorespiratory Parameters

All PPG and breathing data are processed in MATLAB to estimate the cardiorespiratory parameters and each of them are detailed in the following subsections:

3.1 Heart-Rate Calculation

The difference between two consecutive peaks, representing the duration between two consecutive heart beats, of the recorded PPG signals are analyzed to calculate the average heart rate in time domain. The formula for average heart-rate calculation using the PPG peaks is given as follows:

$$HR = \frac{1}{n-1} \sum_{i=1}^{n} \frac{60}{t_{i+1} - t_i}; n \geq 2 \quad (1)$$

where n is the total number of detected peaks and t_i is the i^{th} detected peak, in a given segment of PPG signal.

3.2 Estimation of SpO2

The estimation of SpO_2 require both the red and infra-red wavelength PPG signals and can be given using the following formulas:

$$Ratio = \frac{AC_{Red}/DC_{Red}}{AC_{IR}/DC_{IR}} \quad (2)$$

and

$$\%SpO_2 = \alpha.(Ratio)^2 + \beta.(Ratio) + \gamma \quad (3)$$

Here α, β, and γ are called calibration coefficients and are determined empirically by acquiring data from a large set of people. The values of α, β, and γ are used as −45.060, 30.354, and 94.84, respectively, for $\%SpO_2$ calculation [12]. The estimated $\%SpO_2$ in a healthy subject should always be closer to 100%.

3.3 Breathing Monitoring and Estimation

The PPG signal has also been reported to have breathing information in them and can be used as an indirect method for respiration detection [10, 11]. A way of extracting respiration signal from the PPG signal is by observing respiration sinus arrhythmia (RSA), an event where the beat-to-beat heart rate interval decreases during inhalation and increases during exhalation [10]. Therefore, the peak-to-peak time interval of the heart rate variation (HRV) curve should correspond to the breathing events [11].

Only because of this reason the average heart rate is also calculated in time domain by selecting PPG peak-to-peak distances and thereby determining beat-to-beat heart rates for a given segment of PPG data. The beat-to-beat heart rate data is also known as the heart rate variation i.e. HRV. In the next step, the HRV data extracted from intraoral PPG is then smoothened out and a curve is obtained which can be interpreted as a breathing signal.

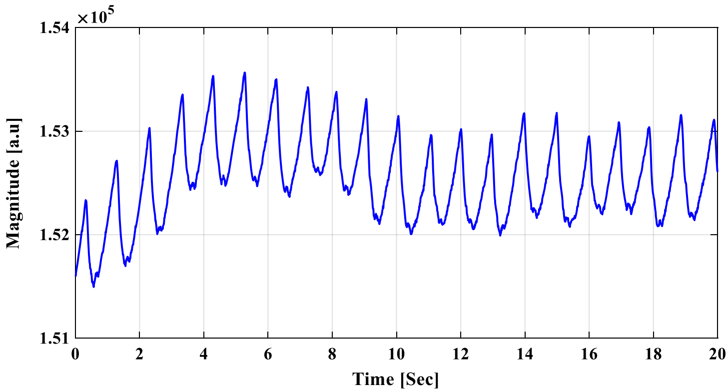

Fig. 3. Example PPG signal recorded intraorally.

4 Results and Analysis

The experimental procedure in this study is in accordance with the Deceleration of Helsinki and was approved by Institutional Review Board of McGill University (study number: A04-M21-19B, approval date: 04/17/2019). In this experiment, the intraoral PPG sensor was wrapped in a transparent plastic material for isolation. The transparent plastic material was safe to use inside the mouth. Several locations inside the oral cavity, like the tongue surface, mouth roof, interior and exterior gum of the upper and lower jaw, and buccal mucosa are tested to obtain a good optimal PPG signal. The locations in the interior part of the oral cavity such as mouth roof are not suitable for the measurement since PPG sensors are sensitive to motion and a slight movement of the tongue disturbs the recording. The exterior gum of the upper jaw could not be tested properly because of the relatively small headroom to place the PPG sensor. The buccal mucosa area facing opposite to both the upper and lower jaw is found to be the best location for PPG sensor placement and the area gets isolated from the tongue when the jaws are closed. Since the PPG sensor did not get affected by any ambient light source inside the oral cavity, very clear PPG signals were recorded. Figure 3 shows an example PPG signal recorded intraorally for 20 s. To further investigate the study, five subjects are tested and PPG signals are recorded for a duration of 1 to 2 min intraorally as well as from their left index fingertip as reference measurement. At the same time as this intraoral PPG signal measurement, breathing signals from a respiration monitoring belt are recorded, simultaneously.

4.1 Validation of Heart Rate

The average heart rates for all five subjects are calculated from the intraoral PPG and the reference PPG signal after selecting the peaks (in MATLAB) and using the formula given in (1). One example of the intraoral and reference PPG signals with their selected peaks (in MATLAB) are shown in Fig. 4. The calculated heart rates for 5 subjects along with absolute error are presented in Table 1, which shows an average absolute error of 0.75% for intraoral PPG signal, with respect to the reference PPG signal.

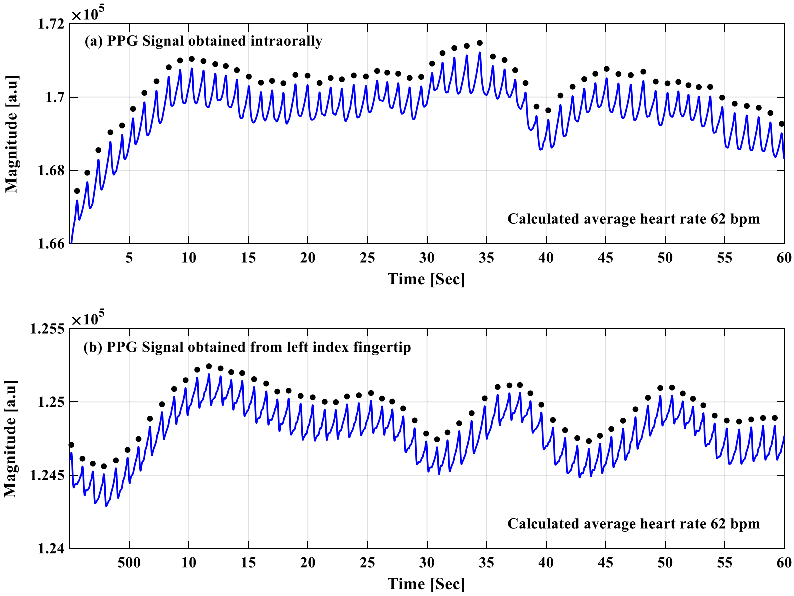

Fig. 4. Average heart rate calculations from: (a) intraoral PPG signal and (b) reference PPG signal taken from the left index fingertip.

Table 1. Average heart rate calculation from intraoral signals and reference PPG signals taken from left index fingertip in beats per minute (bpm).

Subjects	Average heart rate from intraoral PPG (in bpm)	Average heart rate from reference PPG (in bpm)	% Absolute error
1	62	62	0%
2	66	65	1.54%
3	68	68	0%
4	87	88	1.14%
5	92	93	1.08%

Table 2. Estimated %SpO_2 range from intraoral signals and reference PPG signals taken from left index fingertip.

Subjects	Average %SpO_2 range from intraoral PPG	Variation	Average %SpO_2 range from reference PPG	Variation
1	98.75–99.95%	1.2%	97.71–99.95%	2.24%
2	97.65–99.95%	2.3%	99.79–99.95%	0.16%
3	95.76–99.95%	4.19%	97.15–99.95%	2.8%
4	95.97–99.95%	3.98%	99.06–99.95%	0.89%
5	99.55–99.95%	0.4%	99.28–99.95%	0.67%

4.2 Validation of Percentage SpO_2 (%SpO_2)

To estimate the %SpO_2 for all the five subjects, Eqs. (2) and (3) are used. The calculated range of %SpO_2 levels is presented in Table 2 and one reading is presented in Fig. 5. The average variation in %SpO_2 for intraoral PPG signal is calculated to be 2.41%, whereas for the reference PPG signal taken from the left index fingertip is 1.35%.

4.3 Validation of Breathing Patterns

To study the effect of breathing on PPG signals, different breathing patterns like normal breathing, slow breathing, fast breathing, shallow breathing, and breath holds are performed with the subjects. Figure 6 and 7 show the HRV curve obtained from intraoral measurement along with breathing signal obtained from the respiration monitoring belt (standard breathing measurement) during two new tests, separate from the test cases used for heart rate and %SpO2 estimation. This is done to see how the PPG signals respond to different kinds of breathing pattern and if the intended HRV data can capture those patterns. For the test shown in Fig. 6, the subject performed slow breathing (SLB) at first followed by normal (NB), again slow (SLB) and then fast breathing (FB). If we compare the intraoral HRV curve with the standard breathing measurement it can be seen that the HRV curve can properly detect all the peaks for normal and slow breathing. The five

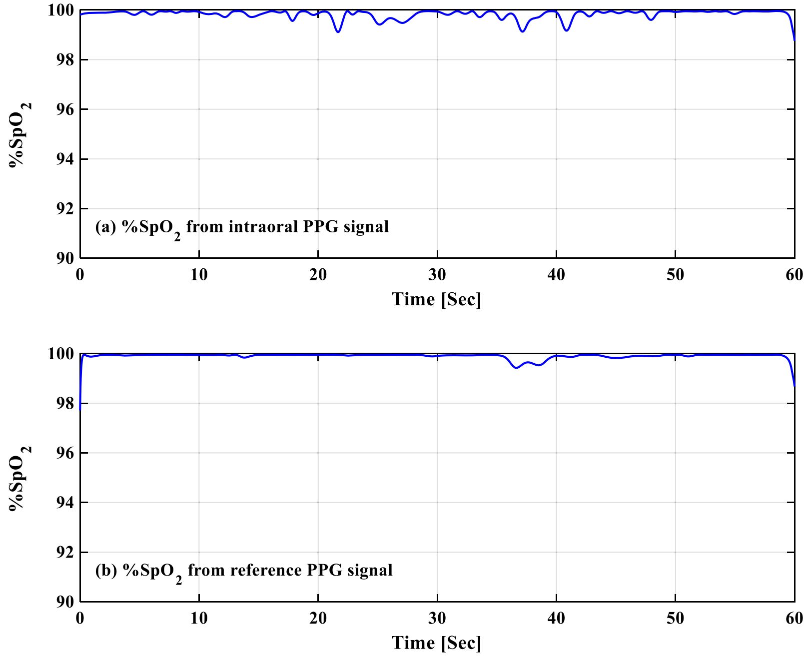

Fig. 5. Estimation of $\%SpO_2$ levels from: (a) intraoral PPG signal and (b) reference PPG signal taken from the left index fingertip.

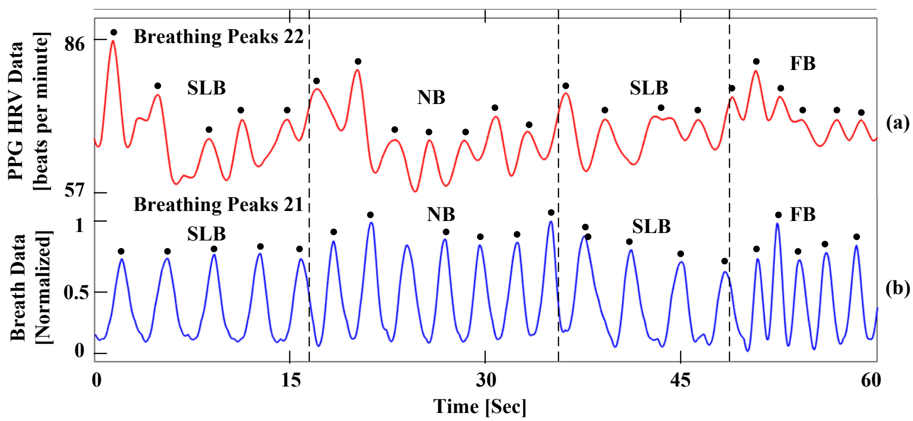

Fig. 6. Respiratory waveforms of a subject: (a) PPG HRV data in beats per minute from the PPG sensor and (b) Normalized Breath data from the respiration monitoring belt, with the following breathing patterns: slow breathing (SLB), normal breathing (NB), and fast breathing (FB).

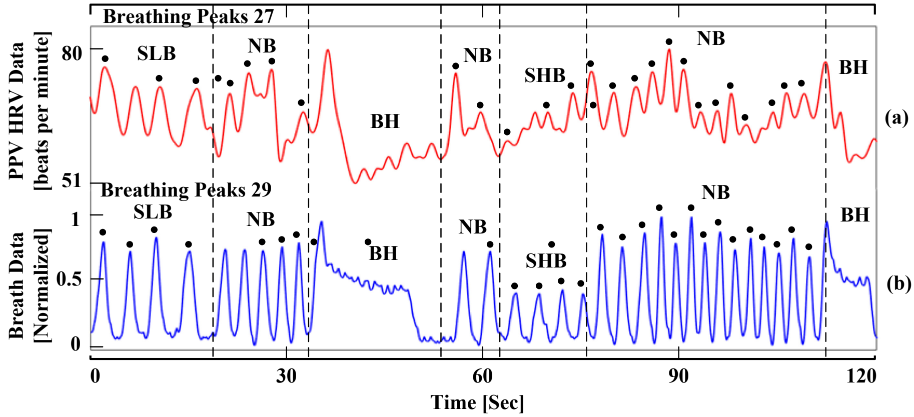

Fig. 7. Respiratory waveforms of a subject: (a) PPG HRV data in beats per minute from the PPG sensor and (b) Normalized Breath data from the respiration monitoring tube, with the following breathing patterns: slow breathing (SLB), normal breathing (NB), shallow breathing (FB), and breath holds (BH).

peaks for the fast breathing pattern are also visible in the HRV curve. However, the peak to valley differences are small for fast breathing in HRV curve in comparison to the other breathing patterns. This behavior is expected since the heart activity does not get much affected during a simulated fast breathing and the gaseous exchange happen in small amount. In some cases, we see dual peaks in the HRV curve for a corresponding single peak in the respiration curve. This is an artifact generated by the MATLAB interpolation function when it sees same heart rate value in the two consecutive points in the discrete HRV data.

For the test shown in Fig. 7, the subject performed breathing patterns as followed: slow breathing (SLB), normal breathing (NB), a breath hold (BH), normal breathing (NB), shallow breathing (SHB), normal breathing (NB), and at the end another breath hold (BH) event. If we compare the intraoral HRV curve with the standard breathing measurement it can be seen that the HRV curve can detect all the peaks for normal, slow, and shallow breathing properly. The amplitude of HRV curve goes down significantly during the breathing hold event and fluctuates very little during the entire breath hold event. This pattern can easily detect a breath hold event (an indicator of sleep apnea patients).

Now, for the test given in Fig. 6, the breathing peaks are counted as 22 and 21 from HRV curve extracted from intraoral PPG signal and the reference breathing signal from the respiration monitoring belt, respectively. Whereas, for Fig. 7, the counted breathing peaks (excluding the breath hold event) are 27 and 29 from HRV curve extracted from intraoral PPG signal and the reference breathing signal from the respiration monitoring belt, respectively. The overall absolute error of this two readings is found out to be 5.83%, thus showing the potential of intraoral PPG measurements in smart MAD technologies.

5 Conclusion

To assess cardiorespiratory parameters during sleep, the intraoral monitoring of PPG signals can be utilized. In this regard, the PPG sensor can be integrated with a mandibular advancement device (MAD) to monitor patients who suffer from obstructive sleep apnea (OSA). This is a non-invasive technique and doesn't require any kind of incision while placing the PPG sensor in the oral cavity. We provide a detailed study of monitoring PPG signals intraorally for extracting cardiorespiratory parameters like average heart rate, $\%SpO_2$, and respiratory (or breathing) events. The estimated heart rate, $\%SpO_2$, and breathing events from the intraoral PPG signal are validated with a fingertip PPG sensor and a respiration belt, respectively. The intraoral heart rate measurement for five subjects provided an average error of 0.75% with respect to the reference PPG measurement. The same readings yielded an average variation of 2.41% in $\%SpO_2$ from the intraoral PPG, whereas the reference PPG yielded an average variation of 1.35%. Different kinds of breathing patterns, such as normal, slow, fast, shallow, and breath-hold, recorded from the PPG signal were compared with the reference measurement. Intraoral measurement were able to capture almost all the breathing peaks intraorally showing an average error of 5.83%. This intraoral monitoring showed the reliability of capturing intraoral PPG signal to detect cardiorespiratory parameters by the MADs.

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