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Development of a sleep apnea event detection method using photoplethysmography

Takuji Suzuki, Ken-ichi Kameyama, Yoshimi Inoko and Toshiyo Tamura, *Member, IEEE*

Abstract— **We studied the possibility of detection of sleep apnea or hypopnea events from photoplethysmography (PPG) wave variation patterns during sleep. In three patients with suspected sleep apnea syndrome, polysomnography (PSG) and the PPG wave were measured simultaneously during sleep. The characteristics of the PPG wave variation patterns in apnea or hypopnea events detected by PSG were investigated. It was found that pulse rate increases and pulse wave amplitude decreases during apnea or hypopnea events, and the respiratory component of heart rate variability has a tendency to decrease before the apnea or hypopnea events. Also, compared to hypopnea, the ratio of the pulse rate is higher, the reduction of the pulse amplitude is more significant, and the decrease of the degree of respiratory variation component in the apnea event is greater. We devised the apnea / hypopnea detection algorithm using these characteristics and evaluated its effectiveness.**

I. Introduction

One in five people in Japan complain of insomnia and sleep disorders are considered an aspect of contemporary life. In particular, sleep apnea syndrome is not only a health problem, causing excessive sleepiness during the day, but also a social issue in that it may cause accidents (train accidents, car accidents, etc.).

Recently, polysomnography (PSG) is used to monitor sleep apnea syndrome by measuring EEG(Electroencephalography), EMG(Electromyography), respiration and the blood oxygen saturation level (SpO2), but it imposes a significant burden on the patient because of a lot of sensors. This has led to initiatives concerning the development of devices that can be used easily at home. In recent years, screening for sleep apnea syndrome has been made possible in the home by using a pulse oximeter to measure the SpO2 during sleep and monitor to detect decreases in SpO2 level owing to apnea events. The use of a pulse oximeter is a simple solution, but pulse oximeters may sometimes fail to detect apnea or hypopnea events, especially in a mild case of sleep apnea syndrome.

We therefore studied the feasibility of detection of apnea / hypopnea events directly based on photoplethysmography (PPG) signal measured by a wearable sleep sensor that we developed. Our goal is to solve the problem of detection failure by pulse oximeters. PPG is blood flow volume in dermis measured by using photo-electric sensor. PPG includes a lot of information about autonomic nervous activity and it would appear that PPG directly reflects the physiological response to apnea events. Also, a PPG sensor is simpler to use in daily life than a pulse oximeter and is low in cost. Gill et al. [3] studied the feasibility of apnea detection by using the amplitude fluctuations (decreases in the amplitude fluctuations of photopletysmography: DAP) of PPG. Penzel et al. [4] also studied an apnea event detection method using the peripheral arterial tone (PAT) signal. However, they used only the amplitude information to detect apnea events and the PAT device is somewhat burdensome as it constricts the patient's finger.

In this paper, we carried out simultaneous measurements of our wearable sensors (PPG) and PSG for subjects with suspected sleep apnea syndrome, and some characteristics of PPG wave corresponding to the observed apnea event were captured. Using these characteristics, we developed an algorithm to detect sleep apnea events and evaluated its accuracy.

II. Data Acquisition Methods

We studied the possibility of the detection of sleep apnea or hypopnea events from PPG wave variation patterns during sleep. PSG and PPG measurements were performed simultaneously during 9 hours of sleep for three subjects (A: an 81-year-old male, B: a 72-year-old female, and C: a 51-year-old male) with suspected sleep apnea syndrome. The experimental procedure was explained to the subjects and written informed consent was obtained from them.

We used a polysomnograph system (Somnostar, Sensor Medics) with a sampling frequency of 200 Hz to record PSG. PSG measured EEG (C1-A2, C2-A1, O1-A2, O2-A1), EOG, chin EMG, ECG, respiration (nose and chest) and SpO2. SpO2 was also used to detect oxygen desaturation events for reference.

Takuji Suzuki and Ken-ichi Kameyama are with Corporate Research and Development Center Toshiba Corporation, Kanagawa, Japan (e-mail: takuji1.suzuki@toshiba.co.jp, kenichi.kameyama@toshiba.co.jp).

Yoshimi Inoko is with The Nippon Dental University School of Life Dentistry, Niigata, Japan (e-mail: yinoko@ngt.ndu.ac.jp).

Takuji Suzuki and Toshiyo Tamura are with the Department of Medical System Engineering, Faculty of Engineering, Chiba University, Chiba, Japan. (takuji1.suzuki@toshiba.co.jp, tamurat@faculty.chiba-u.jp)

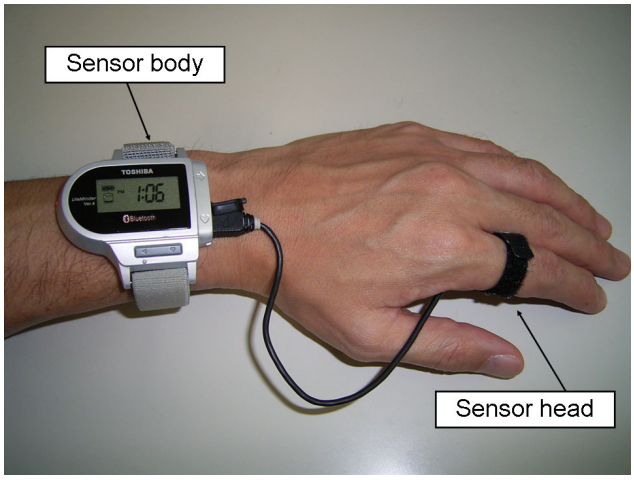

Fig.1 Wearable sensor

We used a prototype wristwatch-style wearable sensor [1][2] (Fig.1) that includes a reflective PPG sensor (wavelength: 525 nm) in the sensor head worn on the finger (for measuring PPG waves) and a 3-axis acceleration sensor (H34C, Hitachi, -3G to +3G) in the sensor body (for measuring body movement). The sampling frequency of the PPG sensor was 64 Hz. The clocks of the polysomnograph and the PPG sensor were synchronized.

Physicians determined Apnea events and oxygen desaturation events by visual inspection of PSG data every 30 seconds.

III. Autonomic Nervous Indicators from PPG

In this study, three indicators derived from PPG waves (pulse rate, pulse amplitude and respiratory variation of pulse wave interval component) were used to investigate the relationship between PPG waves and apnea events.

Pulse rate and pulse amplitude are detected like Fig.2. This method gets maximum and minimum value of pulse wave during the prior 1 second, calculates the internally dividing point between the maximum and minimum value, gets the crossing time and calculates the difference between the crossing time and previous crossing time as pulse Interval. Pulse amplitude is the difference between the maximum and minimum value. Pulse rate is 60 times the inverse of the pulse interval.

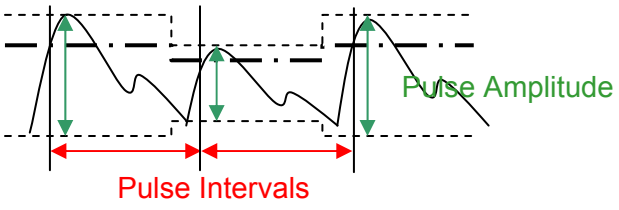

Fig.2 Pulse intervals and pulse amplitude.

We defined mMSSD (modified Means of Sum of the Squared Differences) as an indicator of respiratory variation component of pulse wave interval. mMSSD is based on rMSSD, which is widely used for clinical purposes or physiological studies [5]. This is one of the indicators of autonomic nervous activity by time series analysis. Since normal respiratory interval is about 4 times the pulse interval, the subtraction linear regressive line of 4-point pulse intervals from measured pulse intervals is shown as Fig.3.

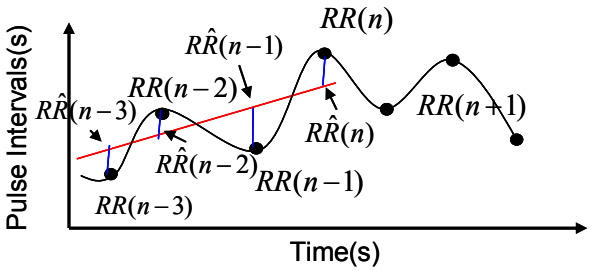

Fig.3 Meaning of mMSSD.

mMSSD is calculated by the following equation (1).

$$mMSSD(n) = \sum_{k=0}^{3} \{RR(n-k) - R\hat{R}(n-k)\}^2 / 4 \qquad (1)$$

$RR(n)$: Measured pulse intervals

$R\hat{R}(n)$: Linear regressive pulse intervals

IV. Results

It was observed that the pulse rate increases and pulse wave amplitude decreases during apnea or hypopnea events, and that the respiratory component of heart rate variability has a tendency to decrease before apnea or hypopnea events. Also, the pulse rate ratio is higher, the pulse amplitude reduction is larger, and the decrease in the respiratory variation of the pulse wave interval component is greater for apnea events than for hypopnea events. Fig. 4 shows an example of the results

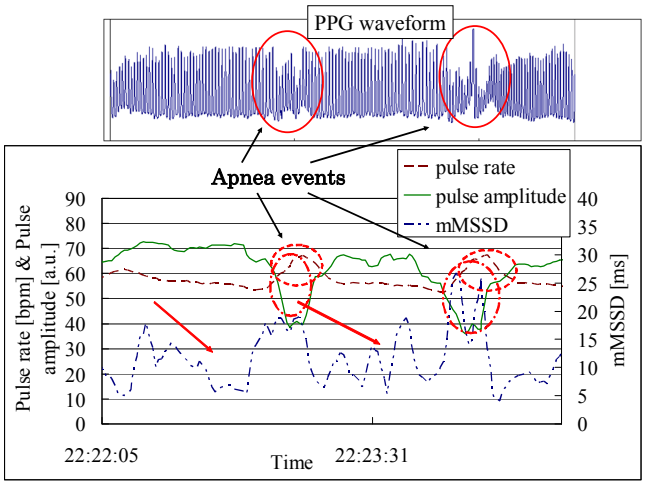

Fig.4 Characteristics of the PPG indicators (red circles indicate apnea events.)

Next, we checked the tendency of each subject.

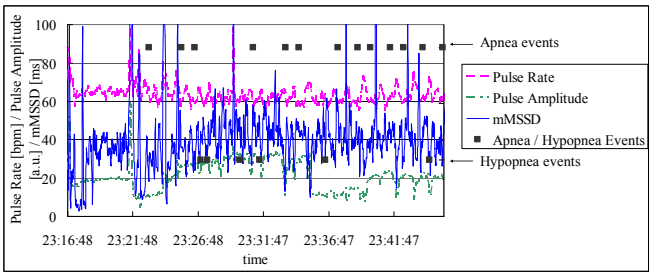

Fig.5 Characteristics of the PPG indicators (subject A: 81-year-old male, AHI[Apnea Hypopnea Index]: 22.8, moderate OSAS)

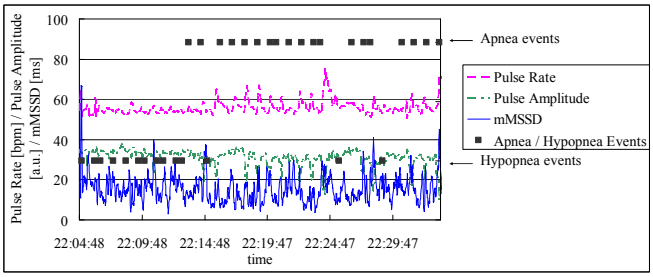

Fig.6 Characteristics of the PPG indicators (subject B: 72-year-old female, AHI: 34.8, severe OSAS)

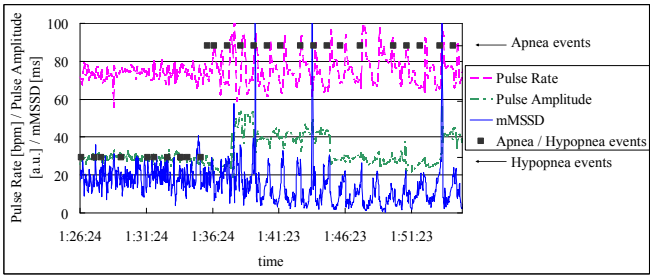

Fig.7 Characteristics of the PPG indicators (subject C: 51-year-old male, AHI: 72.9, severe OSAS)

These results indicate that PPG indicators have common characteristics among the patients.

V. Apnea Event Detection Algorithm

Next, we devised an apnea/hypopnea detection algorithm using the pulse rate elevation, the pulse amplitude decrease and the respiratory variation of the pulse interval component characteristics observed above. Fig.8 shows the flowchart of apnea / hypopnea detection algorithm.

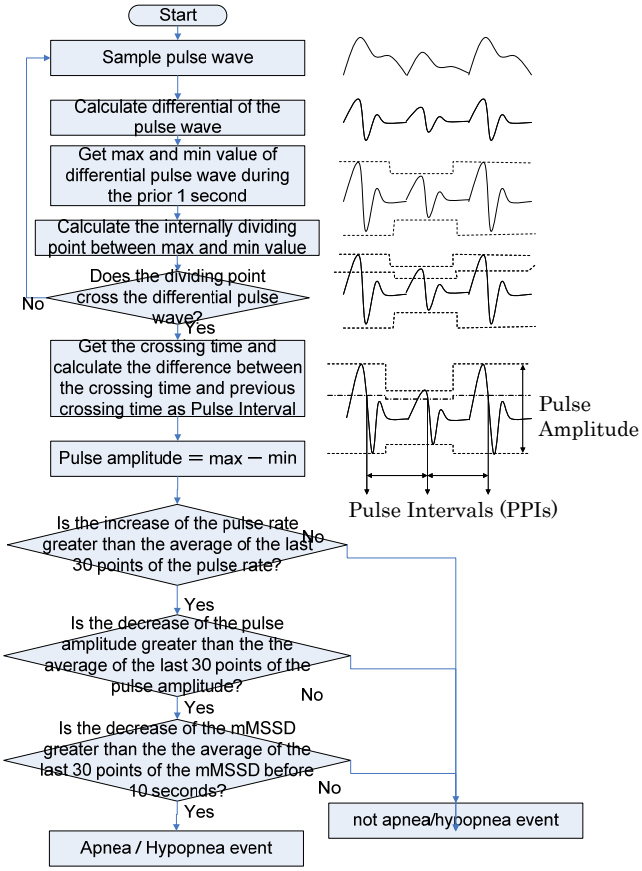

Fig.8 Flowchart of apnea / hypopnea detection algorithm.

VI. Evaluation

Table 1 is an aggregate of apnea events per hour detected in nine hours of sleep for each subject. AHI(Apnea Hypopnea Index) detected from PSG by physician, ODI(Oxygen Desaturation Index) detected from SpO2 by pulse oximeter, and count number of apnea / hypopnea events detected by our method automatically (shown as "Pulse") were compared.

TABLE 1 AHI DETECTED BY EACH METHOD.
(PSG: AHI(APNEA HYPOPNEA INDEX) DETECTED FROM PSG, SPO2: ODI(OXYGEN DESATURATION INDEX) DETECTED FROM SPO2 BY PULSE OXIMETER, PULSE: COUNT NUMBER OF APNEA / HYPOPNEA EVENTS DETECTED BY OUR METHOD.)

	subject A			subject B			subject C		
hour	PSG (AHI)	SpO2 (ODI)	Pulse	PSG (AHI)	SpO2 (ODI)	Pulse	PSG (AHI)	SpO2 (ODI)	Pulse
0-1	4	5	27	22	28	21	47	46	49
1-2	23	25	28	48	53	40	66	62	41
2-3	25	23	25	18	16	20	57	39	55
3-4	39	33	27	45	47	43	56	39	49
4-5	8	10	15	17	16	20	63	79	55
5-6	25	22	18	26	26	45	58	57	56
6-7	0	0	0	13	15	24	36	42	58
7-8	3	1	9	38	39	58	25	32	54
8-9	6	7	34	12	39	27	15	45	29
sum	133	126	183	239	279	298	423	441	446

Our method (Pulse) is slightly overestimated especially in the

second half.

TABLE 2 VALIDATION RESULTS

subject A		PSG		
		Apnea	non-Apnea	sum
Pulse	Apnea	89	41	130
	non-Apnea	44	896	940
	sum	133	937	1070
subject B		PSG		
		Apnea	non-Apnea	sum
Pulse	Apnea	193	53	246
	non-Apnea	46	754	800
	sum	239	807	1046
subject C		PSG		
		Apnea	non-Apnea	sum
Pulse	Apnea	386	60	446
	non-Apnea	37	554	591
	sum	423	614	1037
ALL		PSG		
		Apnea	non-Apnea	sum
Pulse	Apnea	668	154	822
	non-Apnea	127	2204	2331
	sum	795	2358	3153

Table 2 shows validation results. This shows the coincidence between the detection of our method (shown as "Pulse") and the detection of PSG by physician (shown as "PSG") for every 30 seconds. Time periods including an apnea event and those not including one were counted for every 30 seconds for each subject and the overall results. For example, under subject A, the element (1,1) of the table is 89, it means that the number of the detection as apnea both by our method and by PSG.

We evaluated the effectiveness of this algorithm in terms of sensitivity, specificity, and the threat score, which is a measure of the degree of coincidence between the apnea event detection results of the algorithm and PSG. PSG detection is used as right result. The threat score is usually employed in the evaluation of weather forecasts. It is calculated by the following equation (2).

$$ThreatScore = (hits)/(hits + falsealarms + misses) \quad (2)$$

The average threat score for the three subjects was 0.688.

TABLE 3 SENSITIVITY, SPECIFICITY AND THREAT SCORE OF THE OUR METHOD AND DESATURATION BY SPO2.

	sensitivity		specificity		threat score	
subject	Pulse	SpO2	Pulse	SpO2	Pulse	SpO2
A	0.669	0.867	0.956	0.991	0.507	0.898
B	0.808	0.986	0.934	0.969	0.715	0.923
C	0.913	0.926	0.902	0.929	0.843	0.833
ALL	0.796	0.926	0.931	0.963	0.688	0.885

VII. DISCUSSION

Our method is considered to be inherently more sensitive for hypopnea than the pulse oximeter. Consequently, our method detects autonomic nervous activity directly according to the apnea event from the pulse wave. In particular, the respiration component of the pulse intervals (mMSSD) is considered to reflect the cessation of breathing during an apnea event.

However, the accuracy of our algorithm in this study was inferior to that of the pulse oximeter. Since SpO2 measured by the pulse oximeter was used not only for oxygen desaturation detection but also for Apnea / Hypopnea detection, there is a good correspondence between PSG and SpO2. We need to evaluate by using another pulse oximeter that doesn't use in apnea / hypopnea detection of PSG.

We have two plans to improve this result as follows.

One is parameter optimization. In this study, our method used a fixed threshold among the subjects to detect the events. Since the indicators that we used vary, we need to improve the indicators or the algorithm to scale back the influence of the individual variability.

Also, since the indicators that we used were noisy (especially mMSSD), improvement of robustness against noise through parameter optimization to accommodate differences is a subject for future work.

VIII. CONCLUSION

We studied the possibility of detection of sleep apnea or hypopnea events from PPG wave variation patterns during sleep and we developed an apnea / hypopnea detection algorithm using these characteristics and evaluated its effectiveness.

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