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A Study on the Measurement of Respiratory Rate Using a Respirator Equipped with an Air Pressure Sensor

Woochang Shin

Professor, Dept. of Computer Science, Seokyeong University, Korea
wcshin@skuniv.ac.kr

Abstract

In order to measure the respiratory rate, one of the major vital signs, many devices have been developed and related studies have been conducted. In particular, as the number of wearers of respirators increases in the COVID-19 pandemic situation, studies have been conducted to measure the respiratory rate of the wearer by attaching an electronic sensor to the respirator, but most of them are cases in which an air flow sensor or a microphone sensor is used. In this study, we design and develop a system that measures the respiratory rate of the wearer using an air pressure sensor in a respirator. Air pressure sensors are inexpensive and consume less power than the other sensors. In addition, since the amount of data required for calculation is small and the algorithm is simple, it is suitable for small-scale and low-power processing devices such as Arduino. We developed an algorithm to measure the respiratory rate of a respirator wearer by analysing air pressure change patterns. In addition, variables that can affect air pressure changes were selected, and experimental scenarios were designed according to the variables. According to the designed scenario, we collected air pressure data while the respirator wearer was breathing. The performance of the developed system was evaluated using the collected data.

Key words: *Respiration Rate, Air Pressure, Respirator, Electronic Sensor, ESP32, Vital Sign*

1. INTRODUCTION

Since the outbreak of Corona virus disease 2019 (COVID-19), and even now when vaccines and treatments have been developed, respiratory masks are still a necessity in daily life. Respirators are indispensable, especially for medical staff caring for infected patients. Personal protective equipment (PPE) that protects the body, including the respiratory system, is classified into Level-A, B, C, and D according to the standards set by NIOSH [1].

To deal with respiratory infectious diseases, the use of Powered Air Purifying Respirator (PAPR), a Level-A equipment, is desirable. However, PAPR is expensive and uncomfortable to wear, so it is not suitable as equipment for long-term treatment of numerous COVID-19 patients. In order to solve these problems, several studies are being conducted to develop a non-powered hood respirator using a full-face snorkeling mask [2].

One of the difficulties faced by medical staff wearing PAPRs or non-powered hooded respirators is that they tire quickly. By attaching several electronic sensors to the respirator worn by medical staff, biometric

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Corresponding Author: wcshin@skuniv.ac.kr
Tel: +82-2-940-7755
Professor, Dept. of Computer Science, Seokyeong University, Korea

information of the wearer can be acquired from these sensors, and fatigue of medical staff and signs of disease infection can be detected in advance. Through this, in the case of a medical staff with accumulated fatigue or a medical staff showing signs of a respiratory infectious disease, it is possible to protect him from danger by taking appropriate measures.

In addition, for artificial respirators for patients who have difficulty breathing on their own or for industrial respirators for workers working with toxic gases, electronic sensors can be attached to the respirators to continuously check the wearer's biometric information. When the wearer's biometric information shows abnormal signs, safety measures can be taken immediately. Pan et al. suggested embedding multiple sensors into respirators to monitor blood oxygen saturation, heart rate, and temperature [3].

Respiratory rate, one of the main vital signs, is a numerical expression of how many times a person breathes per minute. The average respiratory rate of a healthy adult is 12 to 20 breaths per minute. In general, a low respiratory rate indicates good health, and when the body needs more oxygen due to exercise or illness, the respiratory rate increases. Respiratory rate is the most basic indicator of a person's physical condition along with other vital signs.

In the present paper, we design and develop a system that measures the respiratory rate of the wearer by attaching an air pressure sensor to the non-powered hooded respirator. When the wearer of the non-powered hooded respirator breathes, a change in air pressure occurs within the respirator. Depending on the airtightness of the respirator and the air permeability of the respirator filter, the degree of change in air pressure caused by the wearer's breathing varies, and the sound of the wearer's speech or cough also affects the change in air pressure.

The contribution of this paper is to develop an algorithm that can accurately measure the respiratory rate of a respirator wearer even in abnormal situations such as coughing or talking using a pressure sensor, and also implement a prototype system and verify its performance through experiments.

Section 2 reviews related works. In Section 3, the overall architecture of the system for measuring the respiratory rate of the wearer of the respirator is explained, and the experimental scenario is designed. In addition, the respiratory rate measurement algorithm is briefly described. In Section 4, the air pressure change pattern according to the experimental condition variables is explained, and the performance of the developed system is evaluated to prove its effectiveness. Finally, Section 5 summarizes and concludes this paper.

2. Related Work

Many devices have been developed and related studies have been conducted to measure the respiratory rate of humans.

S. J. Kang et al. [4] and T. W. Ha et al. [5] proposed a non-contact respiration measurement method using IR-UWB (Impulse Radio Ultra-Wide Band) technology.

V. V. Tipparaju et al. [6] attached a differential pressure-based flow measurement sensor to a wearable mask device and measured the air expiratory volume of the wearer during respiration. Since the MEMS (Micro-electromechanical systems) based differential pressure sensor used in this study is sensitive to gravity and mechanical movement, high errors may occur during respiratory tracking if there is no mechanism to compensate for this.

V. C. A. Koh et al. [7] attached a small microphone sensor to a KN95 surgical respirator and measured the respiratory rate by analyzing the breathing sound of the wearer. Respirator wearers did not feel uncomfortable with the microphone sensor attached, and the average error of respiratory rate was estimated to be 2.0 ± 1.3 breaths per minute.

O. Atalay et al. [8] proposed a method for monitoring human respiratory rate using a newly developed textile-based strain sensor. Participants in the experiment wore a respiration belt equipped with a strain sensor on the chest or abdomen and performed various scenarios such as slow breathing and fast breathing. As a result of the experiment, the strain sensor showed a good response in both static and dynamic conditions.

Y.K. Lee et al. [9] and Y.G. Choi et al. [10] also developed a system that measures the wearer's respiratory rate by wearing a belt equipped with a pressure sensor on the abdomen.

D.H. Sim et al. [11] proposed a system that monitors the driver's breathing status by mounting an inertial measurement device on the seat belt. In this system, the respiratory rate of the wearer was measured with a model trained in ResNet (Residual neural network) using Gyroscope data, and the result showed 96% accuracy.

The research by V. C. A. Koh et al. [7] is similar to our study in that it measures the respiratory rate of the wearer by attaching an electronic sensor inside the respirator. However, in our study, the respiratory rate of the wearer is measured by analyzing the air pressure change pattern using a pressure sensor, rather than analyzing the sound of breathing using a microphone. In general, air pressure sensors are much cheaper and consume less power than microphone sensors. In addition, since the amount of data to be calculated in the respiratory rate analysis process is much smaller, it has the advantage that it can be operated in a small-scale and low-power processing device such as Arduino.

3. System Development and Experimental Scenario Design

The overall architecture of the system developed in this study is shown in Figure 1. An electronic sensor that detects air pressure is attached to the inside of the non-powered hooded respirator, and the air pressure inside the respirator is measured while the wearer breathes.

In general, during the breathing process, the internal air pressure decreases during inhalation and increases during exhalation. The respiratory rate of the wearer can be measured by analyzing the change pattern of air pressure inside the respirator. The normal breathing rate of a healthy adult is 12 to 20 breaths per minute. A respiratory rate outside this range can be reported to the wearer. Figure 2 shows the respirators and devices used in the development.

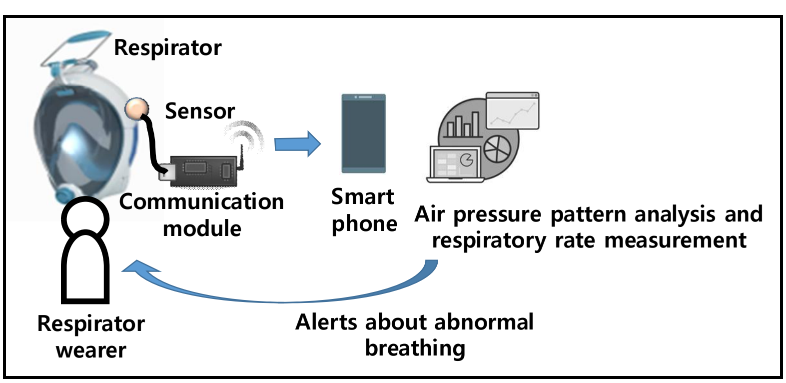


Figure 1. Overall Architecture of Respiratory Rate Measurement System

Figure 2. Respirator and devices

3.1 Development of a Respirator system with an electronic air pressure sensor

In this study, a non-powered hooded respirator developed by a start-up company was used, and the Bosch Sensortec BME680 was selected as an air pressure sensor attached to the respirator [12]. ESP32 developed by Espressif Systems was used to implement a function that is mounted on a respirator and periodically acquires data from the air pressure sensor and transmits it to a smartphone application [13].

A program to control the ESP32 device was developed in Arduino IDE, and this program measures air pressure every 20 msec from BME 680 and transmits the pressure data to a smartphone application through Bluetooth communication. The smartphone application stores the transmitted air pressure data as a local file and then analyses it to measure the wearer's respiratory rate.

3.2 Experimental Scenario Design

When the physical condition of the wearer of the respirator is in a stressful state, the respiratory cycle will be shortened, and when the wearer is in a comfortable state, the respiratory cycle will be long.

If the wearer coughs or speaks while breathing, the air pressure change pattern within the respirator will change. Environmental variables, such as the air permeability of the air filter fitted to the respirator, also affect the air pressure change. However, as a result of a simple preliminary experiment, the air permeability of the air filter affects the average air pressure value in the respirator and does not have a significant effect on the air pressure change pattern, so it was excluded from the experimental scenario conditions.

In this study, we prepare experimental scenarios according to various situations. While the respirator wearer breathes for each scenario, the developed system stores air pressure values over time inside the respirator. The condition variables for configuring the experimental scenarios are shown in Table 1 below.

Table 1. Combination conditions of variables for experimental scenarios

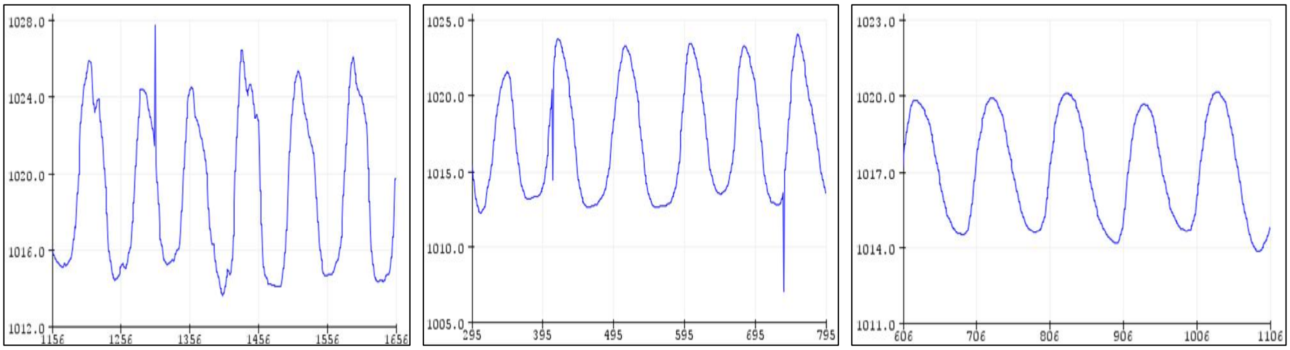
Condition Variable	State
Length of breathing cycle	Normal breathing
	Fast breathing
Cough	No cough
	Cough included
Speech	No speech
	Speech included

By combining the three condition variables shown in Table 1, a total of 6 experimental scenarios are created. After wearing a respirator, the experimenter only breathes at the normal breathing rate for 2 minutes, then breathes including coughing for 2 minutes, and breathes including speech sounds for the last 2 minutes. Afterwards, the experimenter ran for 5 minutes, and then repeated the above three experiments while maintaining shortness of breath.

3.3 Pre-processing of air pressure sensor signal

The signal measured by an air pressure sensor can become noisy due to external disturbances and change rapidly over a short period of time. To compensate for this, the BME 680 sensor provides an infinite impulse response (IIR) filter function. The IIR filter is a recursive filter in that the output from the filter is computed by using the current and previous inputs and previous outputs [14].

The air pressure sensor signal according to the IIR filter setting value is shown in Figure 3. In this study, FILTER_3 was used to minimize the effect of noise on the measured value of the sensor.



(a) FILTER_0 (b) FILTER_1 (c) FILTER_3

Figure 3. Air pressure sensor signal according to IIR filter set value

3.4 Respiratory rate measurement algorithm

The algorithm for calculating respiratory rate from air pressure data consists of the following steps.

Step 1. *Noise removal* - Despite the use of the IIR filter, there are cases where the air pressure value suddenly jumps out of line with the continuously changing air pressure characteristics. Since this is due to noise, we remove it from the measured value.

Step 2. *Signal smoothing* - Smooth the pressure signals from short term overshoots or noisy fluctuations using a moving maximum algorithm. The window size is set to 20.

Step 3. *Redundancy elimination* - Remove continuously redundant values from the smoothed air pressure data.

Step 4. *Finding peaks and valleys* - Find the upper and lower turning points in the air pressure data to calculate the respiratory rate. The lower turning point becomes the starting point of exhalation, and the upper turning point becomes the starting point of inhalation.

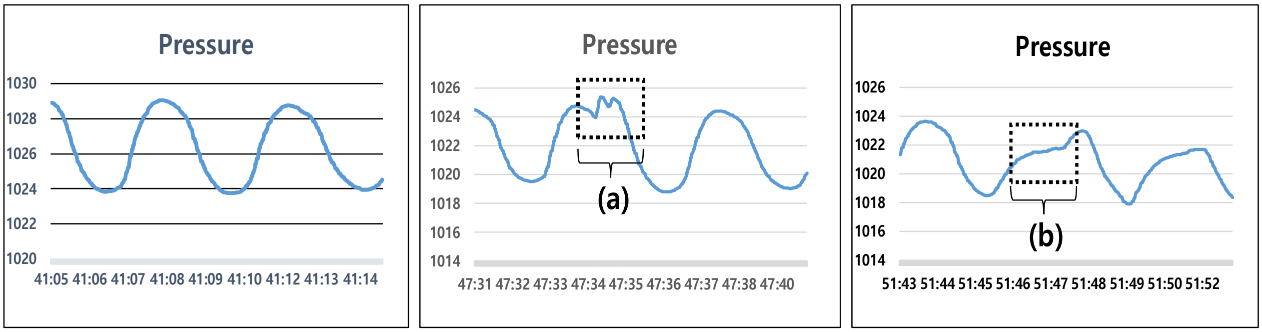
Step 5. *Deletion of local minimum and maximum points* - In order to exclude the case where air pressure changes regardless of breathing due to coughing or talking, the local minimum and maximum turning points are removed. If the difference between the current turning point and the previous turning point is less than 0.5hPa or the time change is less than 0.15 seconds, the current turning point is judged as a local minimum or maximum point.

Step 6. *Respiratory rate measurement* - The upper turning point is the point at which inhalation begins. Respiratory rate is measured by the number of upper turning points within the measurement time.

4. EXPERIMENTS

Three experimenters wore the developed respirators and conducted the experiment for 2 minutes each according to the 6 experimental scenarios.

The air pressure signal patterns are shown in Figure 4 when the wearer of the respirator is (a) breathing only, (b) breathing with coughing, and (c) breathing with speech.



(a) Breathing only (b) Breathing with coughing (c) Breathing with speech

Figure 4. Change patterns of air pressure according to the inclusion of cough and speech

In the case of breathing only, a smooth curve waveform is shown.

When coughing occurs during breathing, a hump-shaped pattern is shown in the soft curve waveform as shown in Figure 4-(b). The hump-shaped pressure change pattern caused by coughing may in some cases appear similar to the pressure change pattern of respiration. However, in most cases, the air pressure change pattern due to cough showed a significantly shorter period and smaller amplitude than the air pressure change pattern of normal respiration.

When speech sounds were included during respiration, as shown in Figure 4-(c), a section in which the change in air pressure slowly rose or descended occurred. If a turning point occurs in such a slowly ascending or descending section, it becomes difficult to measure the respiratory cycle.

Table 2 shows the results of executing the respiratory rate measurement program developed in this study with the air pressure change data obtained according to the 6 scenarios as input.

When the respirator wearer only breathes, the accuracy of the program is 100%. In the case of breathing including coughing, the respiratory rate measurement of the program showed an accuracy of 99.40%, and in the case of including speech sounds, it showed an accuracy of 96.91%. As a result of the experiment, speech was a bigger obstacle to respiration measurement than coughing. Whether the wearer's breathing rate was fast or moderate did not affect the program's respiration rate measurements.

Table 2. Performance metrics for respiration measurement

	Breathing only			Breathing with coughing			Breathing with speech		
	Manual count	Program count	Accuracy (%)	Manual count	Program count	Accuracy (%)	Manual count	Program count	Accuracy (%)
Normal breathing	115	115	100	121	122	99.17	116	119	97.41
Fast breathing	209	209	100	215	216	99.53	208	215	96.63
Total	324	324	100	336	338	99.40	324	334	96.91

5. CONCLUSION

In this paper, we designed and developed a system that measures the respiratory rate of the wearer of the respirator by attaching an air pressure sensor to the non-powered hooded respirator.

6 experimental scenarios were designed depending on whether the respirator wearer's breathing rate was normal or fast, or whether coughing or speaking occurred, and air pressure data were acquired for a total of 36 minutes according to the designed scenarios. We designed an algorithm that measures the respiratory rate of a respirator wearer using air pressure data as input, and implemented it as a program.

As a result of executing the respiration measurement program developed in this study, the respiration rate measurement accuracy is 100% in the case of breathing only, and the accuracy of the entire respiration data including breathing only, cough and speech is 98.78%. Speech was a more difficult obstacle to respiration measurement than the wearer's breathing cycle length or coughing.

Experiments have shown that a small, inexpensive air pressure sensor and a simple algorithm can measure a respirator wearer's respiratory rate fairly accurately, even in the presence of disturbances such as coughing and speech.

By applying the algorithm and system developed in this study, it is possible to build a system that monitors the safety of medical staff or workers related to toxic gases who wear respirators inexpensively and easily.

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