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# Silica Nanoparticle-Based Portable Respiration Sensor for Analysis of Respiration Rate, Pattern, and Phase during Exercise

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**Abstract**— We report a portable respiration sensor for the analysis of respiration rates, patterns, and phases during exercise. A SiO<sub>2</sub> nanoparticle thin film on a flexible substrate is used as a sensor chip (4.1 mm × 5 mm in area of electrodes) to detect respiration. Response and recovery time of the sensor chip are 0.7 and 1.7 s against human respiration. Even when it is covered with water, the response quickly recovers within 1 s after removal of the water. At 5 cm away from a face, a portable respiration sensor can track respiration rates up to 1.7 Hz at rest. The sensor also monitors respiration patterns and phases during exercise noninvasively. The fast-response and portable respiration sensor is usable as a healthcare device.

**Index Terms**—healthcare, respiration sensor, silica nanoparticle, wearable device

## I. INTRODUCTION

Respiration is an essential vital sign for monitoring human health and activity[1], [2]. We can diagnose pulmonary illness by monitoring respiration rates and patterns[3], such as chronic obstructive pulmonary disease[4], apnea[5], and asthma[6]. In hospital, human respiration is usually observed by eyes of medical doctors and nurses. Electrical sensors using transthoracic impedance plethysmography are also widely used[6]–[8]. Since transthoracic impedance plethysmography monitors a small change of tissue volumes by respiration, motion of a target person disturbs the observation of respiration. Therefore, transthoracic impedance plethysmography is only used for patients who do not frequently move, e.g. on bed or at rest.

Recently, respiration during exercise attracts medical scientists. For example, Ishikawa et al. proposed the usefulness of walking test as a screening for pulmonary disease[4]. Respiration is valuable information for athletes to evaluate their performance scientifically[9]. Respiration sensor that can be used during exercise is an important tool for the evaluation. Several new types of respiration sensors have been developed for accurate electrical measurements of respiration[1], [10]. Recently developed wearable respiration sensors are listed in Table 1. Among several sensing mechanisms, in order to avoid the effect of motion of a target person, direct detection of exhaled air is the most promising for sensing respiration during exercise. A paper-based portable respiration sensor has been demonstrated for measuring a respiration rate during walking[9]. The sensor detects humidity of exhaled air directly by measuring conductivity of humid papers placed inside a mask. Although this electrical respiration sensor is portable and low-cost, the system requires digital analysis (such as taking derivation and digital filters) on a software to monitor a respiration rate clearly.

Similar to the paper-based sensor, nanocrystal and nanoparticle-based materials are a candidate for sensing humidity because of the large surface-to-volume ratio[11]. We have recently reported that a thin film of silicon nanocrystals is sensitive to humidity and used for human health monitoring[12]. The response of a thin film is fast enough to monitor human respiration without any digital analysis. A detection mechanism of the sensor is Grotthuss mechanism: water molecules in air adsorb onto oxidized surface of silicon nanocrystals and the amount of water molecules determines the conductivity of the film[13], [14]. The current flows preferentially on the surface of silicon nanocrystals, which is covered with native oxides, and the current through the core of nanocrystals is almost prohibited. This indicates that it is not necessary to use silicon as a humidity-sensitive material. Nanoparticles of any materials with hydrophilic surface can be a candidate for a similar respiration sensor sensing humidity.

Table 1. Recent wearable respiration sensors

Sensing material	Substrate	Mechanism	Ref.
Conductive textile	-	Capacitance	[15]
Silver coated yarn	Textile	Strain	[16]
Piezofilm yarn	Textile	Strain	[17]
Piezoelectric layer	Silicone	Impedance	[8]
Cellulose	Cellulose	Humidity	[9]
Reduced graphene oxide	Polydimethylsiloxane	Humidity	[18]
Silicon nanocrystal film	Polyimide	Humidity	[12]
Chromium/gold	Polyimide and Tegaderm	Strain	[19]
Aluminum (Al)/silicone/Al	Silicone	Strain	[20]
Silver-coated silica glass capillary	-	Antenna	[21]
Al/Polyvinylidene-difluoride/Al	Polyimide	Thermoelectric	[22]
Graphite on paper	Cellulose	Thermoelectric	[23]

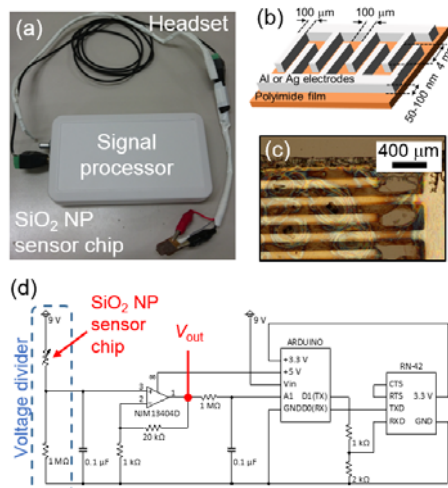
In this work, for detailed analysis of respiration during exercise, we demonstrate a fast-response and portable respiration sensor produced by using a colloidal solution of silica nanoparticles (SiO<sub>2</sub> NPs).

Chemically synthesized colloidal SiO<sub>2</sub> NPs are mass-produced and commercially available as a cheap material.[24] The size of SiO<sub>2</sub> NPs can be tuned down to single-nm with a narrow size distribution and the thin film has a large surface-to-volume ratio. By using the SiO<sub>2</sub> NP thin film, we design a portable respiration sensor system to track human respiration remotely during walking. The portable respiration sensor can monitor human respiration rates in real time. We also show that the sensor response is fast enough to monitor all possible respiration patterns and phases of respiration.

## II. EXPERIMENTAL

Fig. 1(a) shows a picture of a portable respiration sensor designed in this study. The portable respiration sensor consists of a signal processor and a headset with a SiO<sub>2</sub> NP sensor chip. Human respiration can be detected by the sensor chip because the resistance of the film depends on humidity as shown later.

The fabrication procedure of a SiO<sub>2</sub> NP sensor chip is as follows. We adopted a polyimide film as a substrate because of the lightness and the flexibility. A polyimide film 25 or 125- $\mu$ m in thickness was first treated by UV/O<sub>3</sub> for cleaning and improving the hydrophilicity. Aluminum (Al) or silver (Ag) interdigitated electrodes were then fabricated by thermal evaporation with a metal mask. The schematic of interdigitated electrodes is shown in Fig. 1(b). The area of the electrodes is 4.1 mm  $\times$  5 mm with 10 electrode pairs. Following the cleaning of the polyimide film by ultrasonication in acetone and isopropyl alcohol, a 50- $\mu$ L of colloidal SiO<sub>2</sub> NPs (Nissan Chemical Industries Ltd., ST-XS, Concentration: 0.5 mg/mL) was drop-casted and dried at 90 °C. The diameter of the SiO<sub>2</sub> NPs was roughly 10 nm. The average thickness of the film was estimated to be  $\approx$  600 nm from the number of deposited NPs and the area of the interdigitated electrodes. Fig. 1(c) shows an optical microscope image of a sensor chip. Interference fringes are due to the thin film of SiO<sub>2</sub> NPs. The sensor chip is flexible, which is an advantage of a NP film as compared to a thermally oxidized SiO<sub>2</sub> layer on a silicon substrate[25].



**Fig. 1.** (a) Picture of a portable respiration sensor. (b) Schematic of electrodes. (c) Optical microscope image of a SiO<sub>2</sub> NP thin film on electrodes. (d) Electrical circuit of a portable respiration sensor.

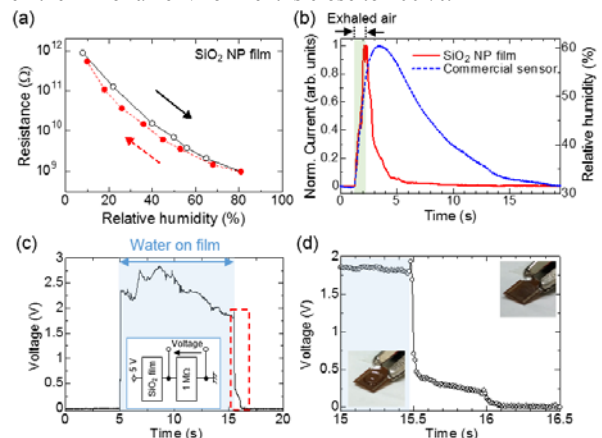
An electrical circuit of the portable respiration sensor is shown in Fig. 1(d). The circuit mainly consists of an operational amplifier

(NJM13404D, New Japan Radio), a microcontroller (Arduino Uno, Arduino), and a Bluetooth module (RN42, Microchip Technology Inc.). The circuit is powered by a 9-V battery cell. A voltage divider consists of a SiO<sub>2</sub> NP sensor chip and a 1 M $\Omega$  resistor. Dynamic range of the respiration sensor is the resistance of a SiO<sub>2</sub> NP film between 20 M $\Omega$  and 20 G $\Omega$  of a SiO<sub>2</sub> NP sensor chip, which is imposed by the readout circuit only.

In the measurements of detailed respiration, subject's respiration was detected by monitoring output of an operational amplifier ( $V_{out}$ ). The acquired data were collected by a PC via wireless communication at 10 Hz with 5 mV voltage resolution. The procedure to collect and display data was written in Processing. The circuit was housed in a plastic box (134 mm $\times$ 75 mm $\times$ 25 mm) as the signal-processor module. Monitoring respiration was demonstrated in 30-70 % of relative humidity (RH). All of the measurements were carried out at room temperature.

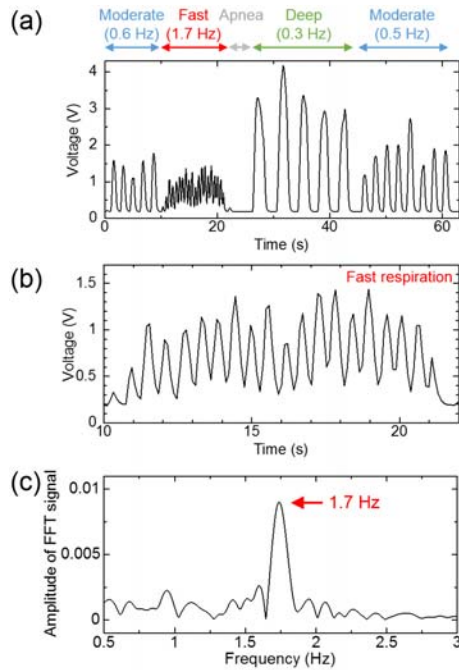
## III. RESULTS AND DISCUSSION

First, we evaluate the performance of the sensor chip. Fig. 2(a) shows the resistance of a SiO<sub>2</sub> NP film in a homemade box at 5 V as a function of RH. RH in the box is controlled by nitrogen carrier gas with bubbling distilled water and monitored by using a commercial humidity sensor (TDK, CHS-UGS, RH accuracy:  $\pm$  5 %). The resistance changes three orders of magnitude in the RH range of 10 and 80 %. This tendency is explained by Grotthuss mechanism[12], [25]. Fig. 2(b) shows the dynamic response of a SiO<sub>2</sub> NP thin film to human respiration. The distance between the sensor and a human face is approximately 10 cm. Exhaled air from the mouth is given to the sensor directly. The simultaneous response of the commercial humidity sensor is shown as a reference. Response and recovery of the signal are faster than those of the commercial sensor are. The response and recovery time of the SiO<sub>2</sub> NP thin film are evaluated to be 0.7 and 1.7 s from the curve, respectively. It should be stressed here that no further digital analysis is required for counting respiration rate by using a sharp peak. Note that the sensor output will be small when the RH of an environment is close to 100 %.



**Fig. 2.** (a) Resistance of a SiO<sub>2</sub> NP thin film versus RH. (b) Dynamic response of a SiO<sub>2</sub> NP film and a commercial humidity sensor to respiration. (c) Response of a voltage divider system when water droplet covers a NP film and (d) Recovery after water removal (a dashed rectangle in (c)). Colored region indicates the time when water droplet covers the SiO<sub>2</sub> NP film.

To evaluate the water-resistance of the sensor chip, 10  $\mu\text{L}$  of distilled water is dropped on the surface by a micropipette, and then removed by air blow. The voltage across a 1 M $\Omega$  load resistor in a voltage divider system (inset in Fig. 2(c)) is measured. In Fig. 2(c), when a water droplet covers the film, the resistance decreases to  $\sim 1$  M $\Omega$  and the output voltage saturates at the value of 2–3 V. The output voltage immediately goes to zero within 1 s when the water droplet is blown off by ambient air (Fig. 2(d)). Heating or other treatments are not necessary to recover the sensor performance after wetting. This fast recovery from a wet condition is an important advantage as a respiration sensor because water fog often appears when deep exhaled air is given.

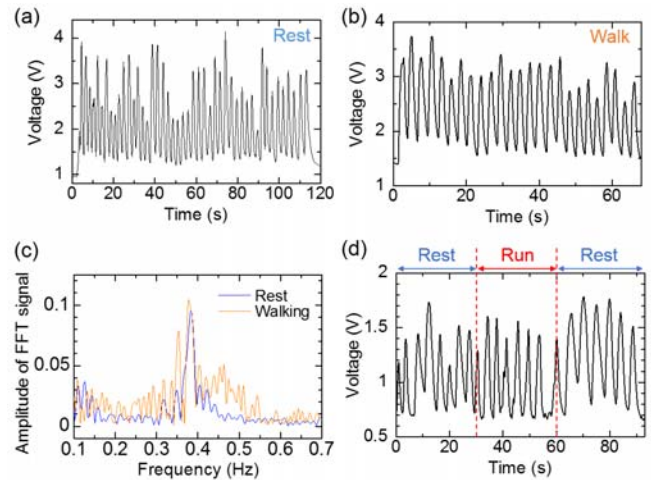


**Fig. 3. (a)  $V_{\text{out}}$  in different respiration patterns at rest. (b) Enlarged response in 1.7-Hz respiration in (a). (c) Frequency spectrum of (b).**

Fig. 3(a) shows the signal of the portable respiration sensor  $V_{\text{out}}$  in different respiration patterns of a subject at rest. In this measurement, the speed and intensity of respiration are intentionally changed. From this experiment, the distance between the sensor and a human face was approximately 5 cm. Exhaled air from the nose was given to the sensor. A respiration rate of normal adult is around 12–15 breaths/min ( $\approx 0.20$ – $0.25$  Hz) at rest[10], and can be up to 60 breaths/min ( $\approx 1$  Hz) by hyperpnoea due to exercise or illness. As can be seen in the respiration pattern designated “Fast (1.7 Hz)” in Fig. 3(a) (and the enlarged figure in Fig. 3(b)), the respiration sensor follows 1.7-Hz respiration. We also confirm that a distinct peak appears at 1.7 Hz in the frequency spectrum by fast Fourier transform (FFT) as shown in Fig. 3(c). This respiration sensor can fully monitor the respiration in hyperpnoea. Apnea is also clearly observed as no signal appears. The respiration rate drastically changes from 0.3 to 1.7 Hz within 60 s in Fig. 3(a), and thus, all possible respiration patterns can be correctly observed by this sensor. The voltage peaks are slightly changed in each respiration rate, which is possibly attributed to the different depth of respiration. The SiO<sub>2</sub> NP sensor chip can be in use as long as the surface is not physically damaged. We have confirmed that the

sensor chip is in use for 6 months.

Fig. 4(a) and 4(b) are respiration patterns of the same subject during a rest for 1 min and walking for 2 min, respectively. The subject takes natural respiration freely. In most individuals during a rest, natural respiration rates and patterns are constant unless there are a large inspiratory effort or a sigh[3]. In Fig. 4(b), respiration during walking is clearly observed as well as during a rest. Frequency spectra of the respiration patterns are shown in Fig. 4(c). In both cases, the highest peak appears at 0.37–0.38 Hz, which indicates that the walking speed is moderate and the respiration rate of the subject is not changed. The sensor can monitor a respiration pattern of a low-intense running (e.g., jogging) subject in Fig. 4(d). This sensor is usable for evaluation of respiration rates and patterns under the effect of exercise.



**Fig. 4. (a-b)  $V_{\text{out}}$  in natural respiration during (a) a rest and (b) walking. (c) Frequency spectra of (a) and (b). (d) Successive monitoring of respiration during a rest and low-intense running.**

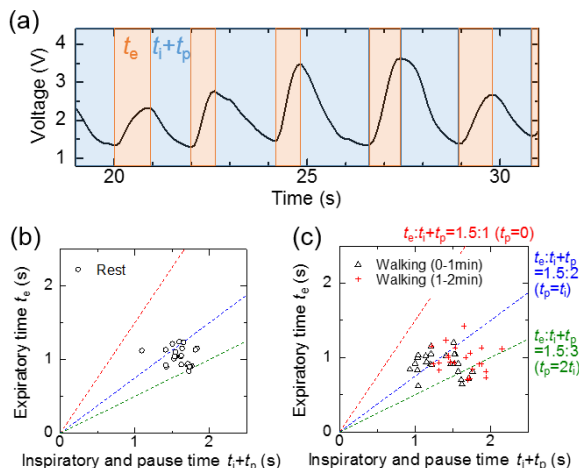
The fast-response sensor allows us to analyze the phases of respiration during exercise. There are three phases in respiration: inspiratory, expiratory, and pause phases. Inspiratory and expiratory phase ratio (I:E ratio) is well known for checking normal human respiration. Phases of respiration at rest have been studied by using conventional methods[5], [26]. However, it has been difficult to evaluate phases of respiration during exercise.

Fig. 5(a) shows the relation of the respiration phases and the output voltage of our sensor. Expiratory time ( $t_e$ ) corresponds to the time of output voltage increase similar to Fig. 2(b). During inspiratory ( $t_i$ ) and pause time ( $t_p$ ), humidity goes back to an ambient value (60–70%RH) and the voltage decreases. Fig. 5(b) and (c) show the relation of  $t_e$  and  $t_i+t_p$  in each respiration during a rest and walking in Fig. 4(a) and (b). The plots distribute around the lines of  $t_e:t_i+t_p = 1.5:2$  and  $1.5:3$ . In a healthy human at rest, it is known that usual I:E ratio is  $t_e:t_i = 1.5:1$ . Thus, the plots lead to the length of the pause time  $t_p = At_i$  ( $1 < A < 2$ ) during a rest and walking. When  $t_p$  is much smaller than  $t_e$  and  $t_i$  (i.e., inhaling and exhaling air are successive and not stopped), the plots move to the red dashed line of  $t_e:t_i+t_p = t_e:t_i = 1.5:1$ , which equals to the usual I:E ratio.

In Fig. 5(c), we distinguish plots of walking respiration into two groups: for the first 1 min (0–1 min) and the second 1 min (1–2 min). Distribution of the plots of walking for 1–2 min appears in the larger  $t_i+t_p$  region. This suggests that the pause time of respiration increases



as the walking test proceeds, which is reasonable because averages of  $t_i+t_p$  in each plot are 1.3 s (0–1 min) and 1.6 s (1–2 min). With the fast-response portable respiration sensor, phase analysis of respiration gives us new information for understanding human respiration during exercise.



**Fig. 5. (a) Analysis of phases of respiration during walking. (b-c) Relation of expiratory time and sum of inspiratory and pause time in each respiration during (b) a rest and (c) walking.**

#### IV. CONCLUSION

We have developed a SiO<sub>2</sub> NP-based portable respiration sensor for the analysis of respiration rates, patterns, and phases during exercise. Colloidal SiO<sub>2</sub> NP is promising for a resistive respiration sensor because of availability and chemical stability. The sensor chip shows fast response (0.7 s) and recovery (1.7 s) to exhaled air. After the removal of water droplet from a NP surface, the voltage divider using a NP film recovers as usual within 1 s. At 5 cm away from a face, a designed portable respiration sensor tracks respiration rates up to 1.7 Hz at rest. The sensor can monitor respiration patterns and phases of respiration during exercise noninvasively.

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