

# **A HIGH RESOLUTION OF HUMAN BREATH GAS SENSOR AND THE ANALYSIS OF HYPERVENTILATION FOR RESCUE ROBOTICS IN DISASTER ZONES (IRIS2010)**

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*Abstract- This paper presents a new type of ultrasonic gas molecule concentration sensor for rescue robotics and the performance of developed sensor is investigated by applying as human breath gas measurement sensor. This device can measure the change of the gas concentration with a sampling rate of 400 kHz. Ideal gas experiment results show that the proposed sensor could detect the difference between 5% CO<sub>2</sub> and pure air over 50 dB S/N and could discriminate humidified air and pure air with 55 dB S/N. Another important result is that our proposed respiratory sensor could detect the "dead space" distributed from lungs to mouth, which could not be detected by previously proposed commercial use gas concentration sensors. Therefore, this sensor can detect a human-specific small-amount of molecular gas change of the survivors in a disaster zones. In addition, we measured the hyperventilation state, in which it is assumed that the survivor is in critical conditions.*

**Index terms:** Human breath sensor, high sampling speed, rescue robotics, hyper-ventilation.

## I. INTRODUCTION

The aim of rescue robotics is to find survivors in a wide area of disaster zones in a short time. Even though previously proposed research paid attention to "survivors sensing", due to technical limitations of existing commercial sensors and analytical methods, the development of more practicable survivor's sensing technique was demanded. There are two big problems of survivor's finding in disaster zones. The first problem is the time limit. The time limit is 72 hours, which is

called as the golden time during which the survivor is still alive in a disaster zone. The second problem is the large area size of the disaster zone, especially during the earthquakes. For example, in the case of Kobe earthquake, over 500 m<sup>2</sup> was destroyed or covered by fire. This means that it is necessary to search for survivors all over the disaster zone in a very short time. In [1], the authors discussed a method of exploring the environment by the visual information and by recognition of the survivor's voice. In [2], the authors proposed the technique of catching body temperature with thermo-gram. This method, however, requires the analysis of pattern matching of the survivor's temperature distribution using thermo-gram image. This difficulty is almost the same with camera visual information and also voice recognition method.

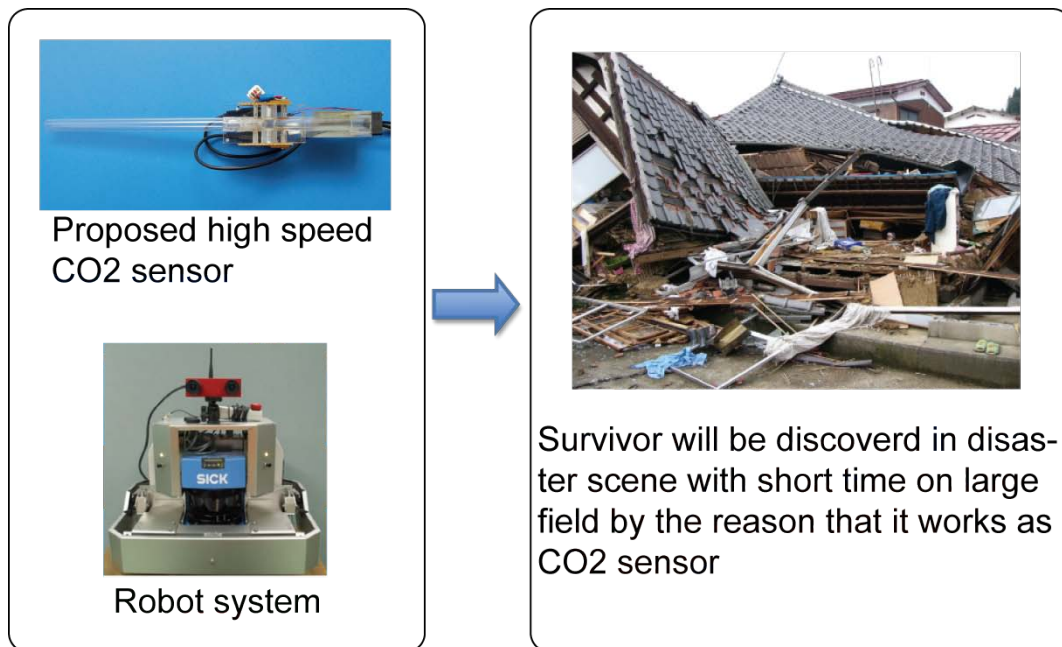


Figure 1. Combination of robotics system and our developed high-speed CO<sub>2</sub> sensing system.

Another survivor's finding method is to selectively detect carbon dioxide (CO<sub>2</sub>) that human body breath out. This method requires to be used together with other methods such as the temperature or image processing. Therefore, from the view point of detection time and data processing, the discovery of the early survivors is difficult.

In this paper, we propose a new type ultrasound high-speed gas sensor, which is able to detect the concentration of gas with high sensitivity and stability. This sensor is firstly developed in the National Institute of Advanced Industrial Science and Technology.

This paper is organized as follows. First, we describe our proposed new gas sensing device in section 2. Then, the performance of the gas concentration sensing device is evaluated using artificial respiratory gas, which contains 5% CO<sub>2</sub> gas with dry air. Finally, we give some results on measurement of the human breath waveform with high-sampling rate. In addition, we measured the hyperventilation state of human breath, which is measured when the survivors is in the critical conditions. The results show that our proposed method for human respiration detection is useful for the survivor detection in large disaster area because our proposed gas sensor can detect the peculiar changes of human respiration.

## II. THE DEVICE

Figure 2 shows the fabricated respiratory gas sensing system. We used a MURATA-MA400A1, 400 kHz piezoelectric ultrasound unit (Murata Manufacturing Co.) where the transmitter and receiver were arranged face to face with a 6-mm gap. The propagation direction of the ultrasound is perpendicular to that of the gas stream, and the ultrasound units and gas stream space are enclosed within acryl chamber.

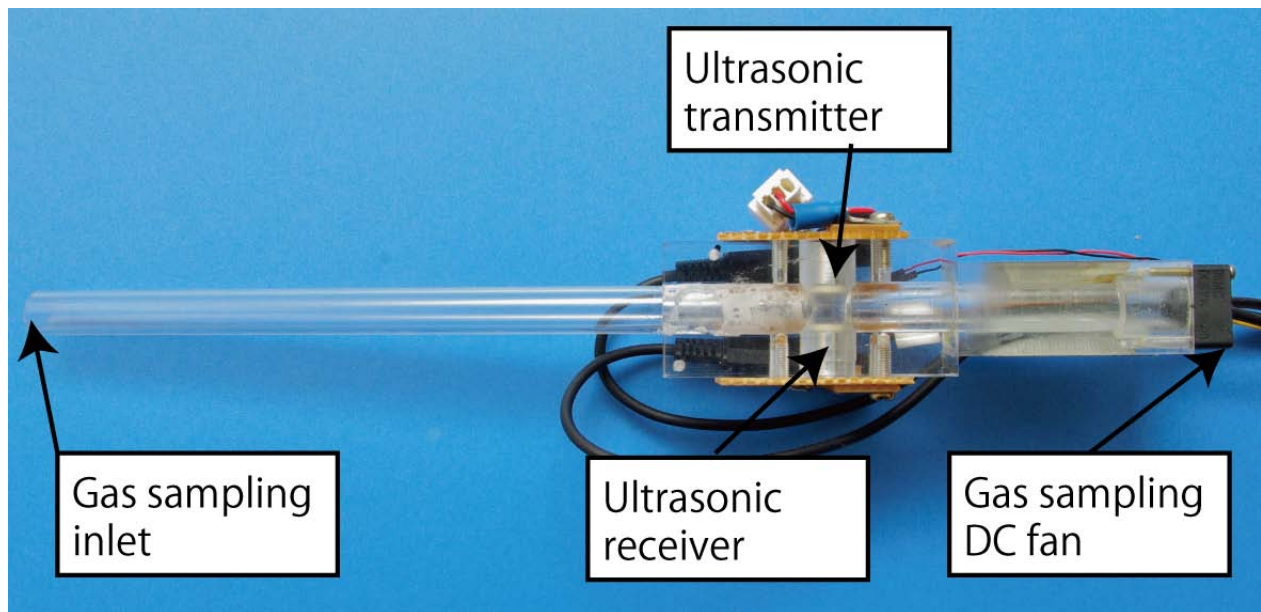


Figure 2. Our developed ultrasonic gas sensor.

Ultrasound transmitter and receiver arranged face to face, and gas stream crosses perpendicularly between the ultrasound sensors. Small gas flow is generated by the D.C. small fan (F16EA, COPAL ELECTRONICS, brushless) attached with the terminal of the gas flow 6mm diameter acryl pipe.

The detailed gas detection performance of the ultrasonic gas sensor is described in [4, 5].

Specific features of this sensor are:

- Gas sensor uses 400 kHz carrier frequency of ultrasound;
- Sampling and gas analysis rate is 1kHz;
- Ability of measuring the change from pure air to a mixture of 5%CO<sub>2</sub> with a 50 dB S/N ratio. under the situation of the distance of the ultrasonic transmitter and receiver is about 6-mm by using 400 kHz ultrasound.

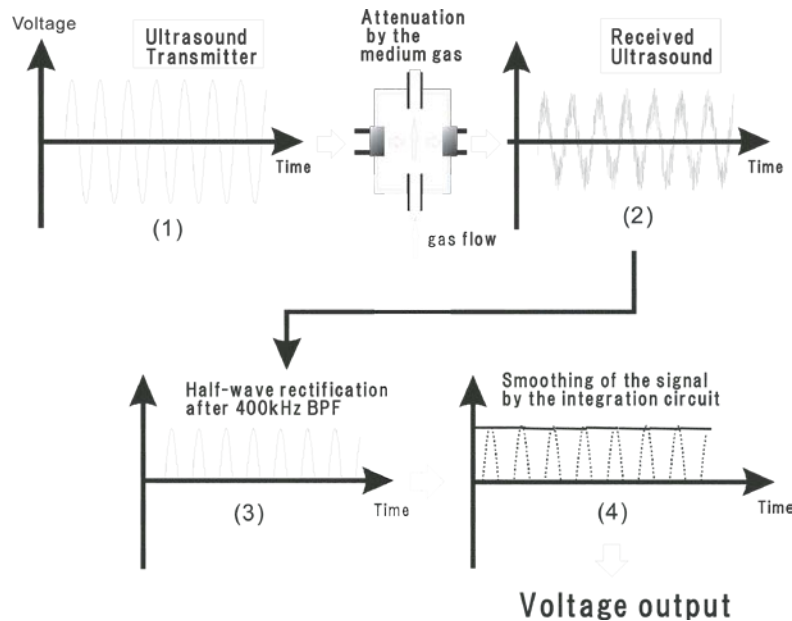


Figure 3. Signal processing diagram of the proposed ultrasound gas concentration sensor. (1) Ultrasonic transmitter generates 400 kHz ultrasonic. (2) Ultrasonic receiver detects the ultrasonic amplitude after the ultrasound passes through the sample gas. (3) The received ultrasound signal was amplified by operational amplifier and we modified the ultrasound signal by half-wave rectification after 400 kHz BPF. (4) By using Peak-Hold circuit, we could detect the height of the

ultrasound amplitude itself. In addition, the signal was smoothed by an integration circuit for reducing the noise.

Precise signal processing flow is shown in Fig.3. By using the signal processing flow, our proposed ultrasonic gas sensor detects the wave amplitude of the received ultrasound wave. This means that if a 400 kHz ultrasound is used as carrier frequency, the time constant of the gas analysis time is 400 kHz. In our sensor, we added an integration circuit, which makes it possible to detect 1 kHz gas sampling. Gas concentration measurement principle is as follows: begin through within the sample gas, the ultrasonic is attenuated by thermal molecular motion of the target gas. There are three factors - temperature, average molecular weight and pressure, which influence the ultrasonic attenuation. However, the main physical factor is average molecular weight since the temperature and pressure are the same with the open air.

Basically, our proposed gas concentration measurement system can detect the difference of the molecular weight of the target gas. Precise physical process and mechanism is more complicated than we have already described above. More precise mechanism of our proposed gas concentration detecting mechanism was described in [4] [5].

### III. IDEAL GAS EXPERIMENT OF OUR PROPOSED GAS SENSOR

Figure 4 shows the experimental setup. We prepared  $5\% \pm 10^{-3} \%$  (V/V) CO<sub>2</sub> contained air bag as an artificial human respiratory gas and humidifier connected to open air. 5% CO<sub>2</sub> gas, humidifier and open terminal to outside air are connected with a four way valve and we can change the connected kind of gases by the valve.

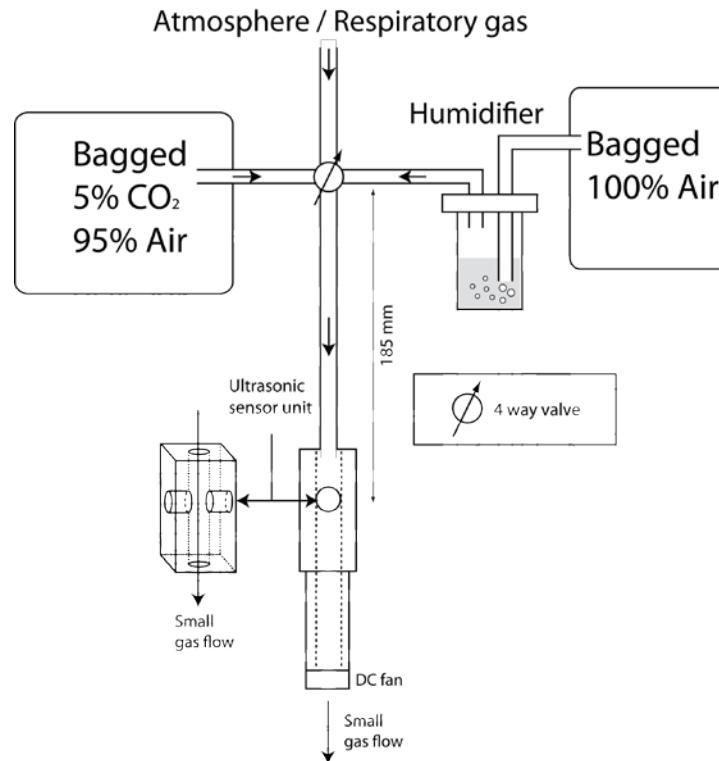


Figure 4. Gas exchange experiment setup of developed sensor for artificially generated respiratory gas and another gas factor for human respiration process.

Figure 5 shows the performance of gas sensor as the gas exchange. Proposed respiratory sensor can detect 5% CO<sub>2</sub> contained gas about 0.5 V larger than the output voltage of air region. The voltage becomes negative when humidified air is tested.

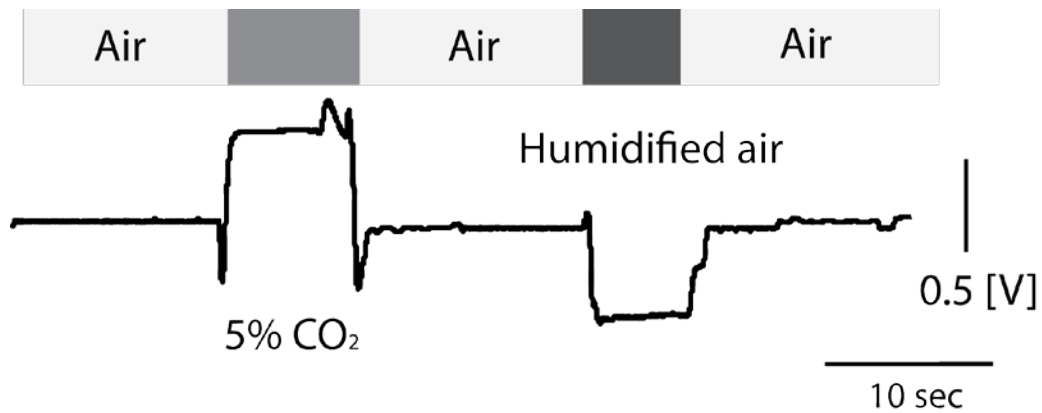


Figure 5. Gas exchange experiments of developed gas sensor. Vertical axis represents output voltage and horizontal axis the elapsed time.

Important point of this experiment is the voltage reversal. Since the output voltage of the ultrasound sensor depends on the average molecular weight of the target gas, it means that there are average molecular weight differences between dry air, humidified air and 5% CO<sub>2</sub> contained air.

Theoretically, at 20 degree Celsius, the average molecular weights of 5% CO<sub>2</sub> contained air is  $44.01 (\text{CO}_2) * 0.05 + 28.97 (\text{Air}) * 0.95 = 29.72$ , dry air is 28.97 and humidified air is  $18.0 (\text{H}_2\text{O}) * 0.023 (\text{saturated vapor}) + 28.97 (\text{Air}) * (1-0.023) = 28.71$ . We conducted experiments in 20 degree Celsius, and the average molecular weights are exactly the same with the theoretically calculated ones. The voltage transition (Fig.5) shows a correspondence with the average molecular weight (a lower voltage corresponds to a lower average molecular weight).

#### IV. RESPIRATORY EXPERIMENT

During the experiment, the subject was wearing the sensor all in one design gas mask. This gas mask is designed so that the expiration gases from the mouth and the nose are collected (Fig. 6). We measured normal respiratory transition pattern in rest state for 6 seconds (sampling time is 1 kHz). The results are shown in Fig.7.

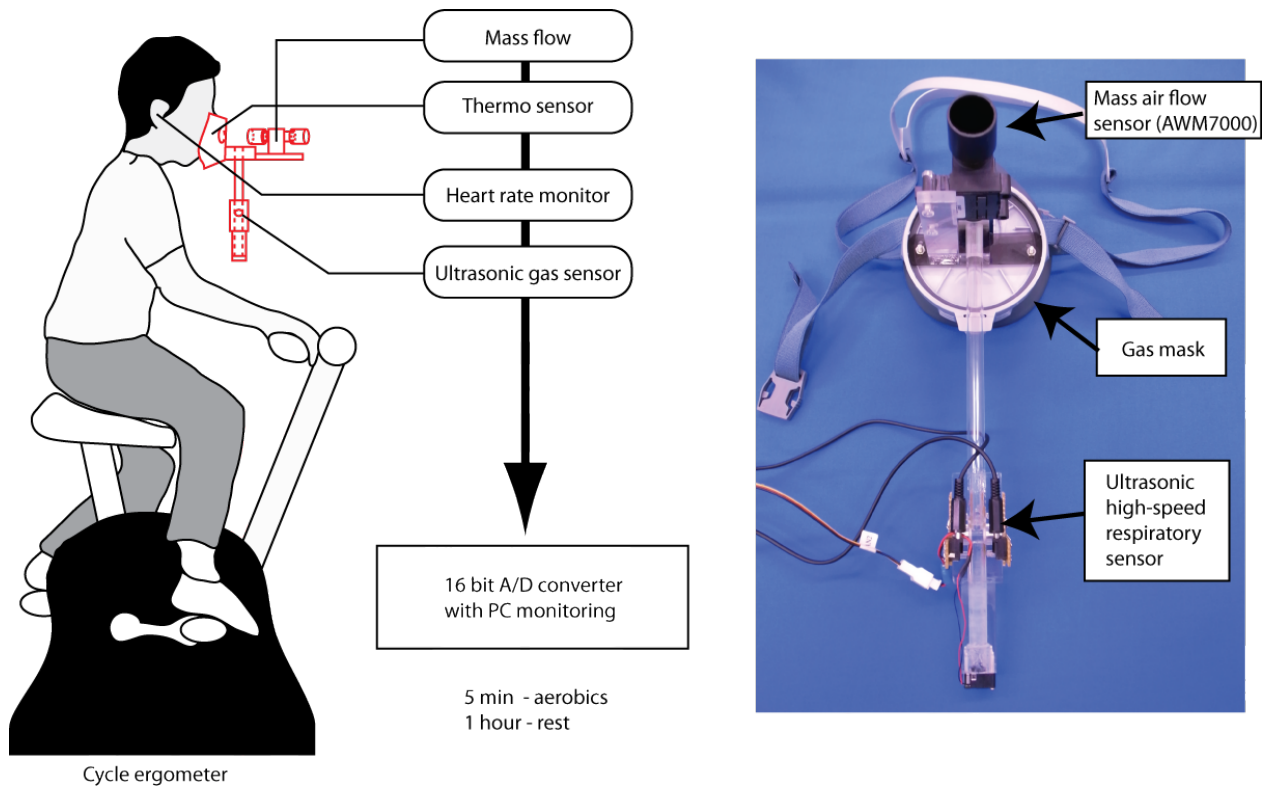


Figure 6. Gas exchange experiment setup of developed sensor for human respiration

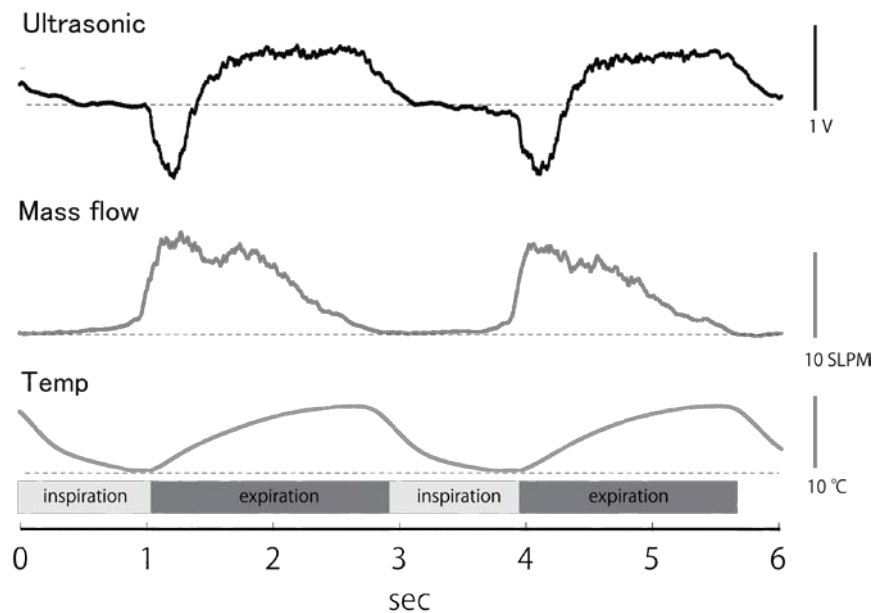


Figure 7. Six seconds respiratory transition at the rest state. (a) Output of our developed respiratory gas sensor. (b) Output of mass flow gas sensor. Mass flow sensor detects total air flow of human respiration. In addition, this sensor just can detect the air flow of expiration phase not

inspiration phase because the direction of air flow measurement is one-way limited. (c) Output of temperature respiratory sensor. Gas analysis time of the temperature sensor is about 400msec. In this graph, we can only see the phase of the inspiration and expiration.

The graph in Fig. 7 shows the output of our developed ultrasonic gas sensor (upper), mass air flow sensor (middle) and temperature respiration sensor (lower). Time constant of each gas sensor are as follows: 1msec - our developed ultrasonic gas sensor, 6msec - mass air flow sensor and 400msec - temperature respiration sensor. Mass flow sensor detects total air flow of human respiration. In addition, this sensor can just detect the air flow of expiration phase not inspiration phase because the direction of air flow measurement is only one-way. Lower graph shows the output of temperature respiratory sensor. We can only see the phase of the inspiration and expiration because of the gas analysis time. As the mass flow increases, first the ultrasonic respiratory sensor starts to change. Since the flow rate of the mass flow sensor is calibrated by gas temperature, the measurement value means, basically, the air flow rate itself. The transition of the mass flow sensor output is not smooth during the expiration. It is important to notice that as the mass flow increases, the ultrasonic sensor output decreases for about 300 msec and then the output increases to the convergent plateau value with some vibrations. This down-up change of the ultrasonic sensor can be seen in any subject at rest state during the experiments. By analyzing the mass flow sensor output, we can see that this down-up change does not depend on an air flow change. In addition, the ultrasonic sensor output represents only the molecular weight change and it does not depend on the air flow change since the ultrasonic sensor output takes some values different from zero (zero values are indicated by dotted line in Figure 7) even when the mass flow sensor output settled to zero value. In our developed ultrasonic gas sensor, we utilized the characteristic that the ultrasonic sensor output depends only on average molecular weight under the condition of constant pressure and temperature. A more detailed explanation is given in [4] [5]

As can be seen from Fig. 6, the down-up phase of the ultrasonic sensor output is related with some instantaneously decrease-increase of average molecular weight. The average molecular weight increasing can determine a phase of CO<sub>2</sub> (Fig. 5). On the other hand, the decreasing of

average molecular weight (down-up phase) will be able to determine a phase of vapor, which is the humidified air. We have already showed that the ultrasonic sensor output decreases in the phase of humidified air and it is related with the fact that the average molecular weight of humidified air is smaller than that of dry air (Fig. 5). Because there is no smaller molecular weight factor, except of the humidified air, than a molecular weight of the air in the path from lung to mouth, we concluded this down-up phase as "dead space" from lung to mouth. Generally, the volume of the small area named dead space is about 0.15 liter in adult man, and this small space is believed to drops the efficiency of the gas ventilation.

## V. RESPIRATION PATTERN OF HYPER-VENTILATION

In this section, we show the peculiar case of human respiration – hyper ventilation. This waveform was able to measure in the situation of an aero bike experiment when the subject female person G.N. executes aerobics (Fig. 6). By comparing with Fig. 8 (a) and (b), we can find that there are two large differences. First is respiration period. About 3.4 (=17/5) times repeated patterns are measured by comparing Fig. 8 (a) and (b). It means that by the reason that the subject have some difficulties of her respiration, she have increased the number of respiration to improving the amount of inhalation of oxygen. Second point is the waveform changes. We can see clearly the difference of (a) and (b). Important changes of the waveform of (b) is that there is only CO<sub>2</sub> fast exchange processes since the wave is on the above line of zero (zero voltage means the molecular weight of Air). This means that the expired gas of the subject does not contain the humidified air, the path of the lung to mouth is filled with CO<sub>2</sub> and there is no humidified air in the path. On the other hand, since the oxygen contained air (means humidified air) cannot reaches to the lung, the efficiency of the gas exchange process of the subject is decreasing. Previously proposed and developed commercial use of respiration sensing system can not detect this precise hyperventilation process by the reason of the analysis time. All the cases, previously proposed respiration sensing system cannot follow this high speed gas molecular weight transition of the hyper-ventilation. Necessity of analysis time of the hyper-ventilation is about 3 msec at least (if we want 100 voltage points of one respiration, 6 sec / 17 respiration / 100 points = 3.5 msec sampling time is needed). Our proposed gas sensing system can easily realize it

(analysis time of our proposed system and previously proposed respiration monitor are 1 msec and 100 – 200 msec respectively ).

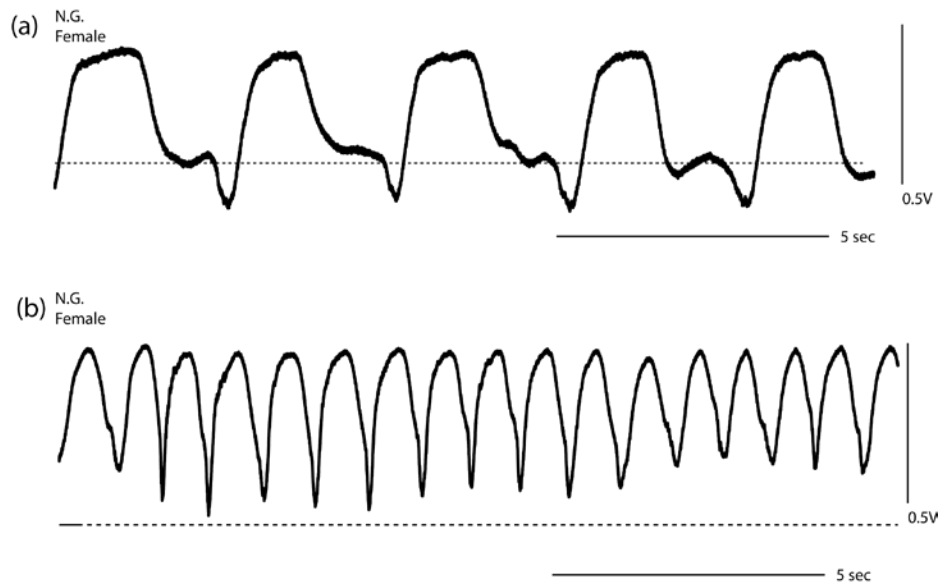


Figure 8. Hyper-ventilation case of breath measurement. (a) Normal respiration pattern of a female person. Within 6 sec, we can see 5 respiration patterns. (b) Graph represents in the case of hyper-ventilation of the same person (a) when the subject executes the aero bike movement.

In order to detect the aerobic state of the subject, we measured the heart beat rate. The experiment stopped after 5 minutes because of the high value of the subject heart beat rate. The analysis of the gas exchange pattern shows that the hyper-ventilation patterns start 1 or 2 min before the experiment stopped because of the heart beat rate change.

This peculiar waveform transition of our proposed gas sensor for the human respiratory process, which has not reported so far by other gas sensors, will be useful for early finding of the survivors in the wide area of disaster scenes because this waveform is a human specific pattern.

## VI. CONCLUSIONS

In this study, we developed an ultrasound based human respiration gas concentration sensor. We confirmed that this sensor can detect the high-speed changes of CO<sub>2</sub> and humidified air with a

one-millisecond temporal resolution. In this process, we found that the sensor output changes from the start of expiration by first decreasing and then increasing immediately in a very short time. It was believed that this is related with the "dead space", which is the small area from the lung to the mouth. This peculiar waveform transition of our proposed gas sensor for the human respiratory process, which has not reported so far by other gas sensors, will be useful for early finding of the survivors in the wide area of disaster scenes. In addition, we can measure the hyper-ventilation process of human respiration in our experiment which is measured when the survivors is in the critical conditions. For the application of rescue robot systems, we want to develop a new analyze algorithm for the peculiar human respiration waveform which was measured by our proposed ultrasonic gas concentration sensor in the next step.

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