Noninvasive Biological Sensor System for Detection of Drunk Driving

Kohji Murata, Etsunori Fujita, Shigeyuki Kojima, Shinitirou Maeda, Yumi Ogura, Tsutomu Kamei, Toshio Tsuji, *Member, IEEE*, Shigehiko Kaneko, Masao Yoshizumi, and Nobutaka Suzuki

***Abstract*—Systems capable of monitoring the biological condition of a driver and issuing warnings during instances of drowsiness have recently been studied. Moreover, many researchers have reported that biological signals, such as brain waves, pulsation waves, and heart rate, are different between people who have and have not consumed alcohol. Currently, we are developing a noninvasive system to detect individuals driving under the influence of alcohol by measuring biological signals. We used the frequency time series analysis to attempt to distinguish between normal and intoxicated states of a person as the basis of the sensing system.**

***Index Terms*—Biological signal, driver behavior, drunk driving, safety, time series analysis.**

I. Introduction

THE most common factors in traffic accidents caused by human error are driving under the influence of alcohol, drowsiness, and inattention, also known as the "Big Three." In order to eliminate these factors, a wide variety of research have been conducted on systems for monitoring drivers' biological signals such as electroencephalography (EEG) (sleepiness in driving) [1]–[3], motor behavior, divided attention, and/or mental workload under the influence of alcohol [4]. But, few reports have addressed noninvasive methods for monitoring the condition of a driver.

Moreover, the breath–alcohol concentration measurement, the present widely utilized methodology to prevent drunk driving, is not able to stop drinking of alcohol after one starts driving. Breath alcohol ignition interlock devices reduce recidivism by 40–95% as long as the interlock remains on the car [5]. Then, we are trying to invent a novel system for monitoring drivers noninvasively and detecting the drivers' drinking after they start driving.

Therefore, we have constructed a seat incorporating an air-pack sensor that can be retrofitted into an existing automobile seat and reported the capabilities of this seat for noninvasive detection of impairment of a driver who has consumed alcohol [6]–[8]. The sensor system in the seat has since been improved. Biological signals, such as body-trunk plethysmogram and respiration, were detected from the back of the driver using the air-pack sensor, a noninvasive and nonconfining method. The extracted body-trunk plethysmogram signal was defined as an air-pack pulse wave (AP-PW). An algorithm for the detection of alcohol-impaired driving was generated from investigations of the AP-PW.

The physiological and psychological condition of a human changes continuously, so a method with high temporal resolution should be used to capture the biological signal changes. Time series analysis is well known as a sensitive method to avoid a lowering of the temporal resolution in signal analysis [9], [10].

Therefore, this study proposes a new algorithm of the frequency time series analysis to distinguish between the normal and intoxicated states of a person.

II. Experimental Method

A. Experimental Apparatus

A seat containing the air-pack sensor used to monitor the AP-PW of a subject is shown in Fig. 1. The digital pulse volume, using a finger clip photoplethysmograph (SR-5C, Amco K.K.), and the breath–alcohol concentration (ALC-mini, Tokai Denshi K.K.) were measured with the AP-PW, simultaneously.

B. Experimental Method

Four subjects participated in this study. The subjects were healthy adults (Subjects A, B, and C were males, and Subject D was female) aged 20–22 years (mean age: 21.0 years). The

Manuscript received April 29, 2010; revised October 14, 2010; accepted November 1, 2010. Date of publication November 11, 2010; date of current version January 4, 2011. This work was supported in part by the Fundamental Research Promotion Program in the Field of Transportation (2004-02) of Japan Railway Construction, Transport and Technology Agency (JRTT).

K. Murata is with the Department of Molecular Reproductive Biology, Kanazawa University, Graduate School of Medical Science, Ishikawa 920-8641, Japan, and also with the Division of Medical Research, Shimane Institute of Health Science, Shimane 693-0021, Japan (e-mail: murata6600@go9.enjoy.ne.jp).

E. Fujita, S. Kojima, S. Maeda, and Y. Ogura are with Deltatooling Company Ltd., Hiroshima 739-0038, Japan (e-mail: gonzo@deltatooling.co.jp; skojima@deltatooling.co.jp; mag.maeda@deltatooling.co.jp; ogu@deltatooling.co.jp).

T. Kamei is with the Institute of Transcultural Health Studies, European University Viadrina, 15230 Frankfurt (Oder), Germany, and with the Nagasaki University Graduate School of Biomedical Sciences, Nagasaki 852-8523, Japan, and also with the Division of Medical Research, Shimane Institute of Health Science, Shimane 693-0021, Japan (e-mail: ttm@fork.ocn.ne.jp).

T. Tsuji is with the Faculty of Engineering, Hiroshima University, Hiroshima 739-8527, Japan (e-mail: tsuji@bsys.hiroshima-u.ac.jp).

S. Kaneko is with the School of Engineering, The University of Tokyo, Tokyo 113-8656, Japan (e-mail: kaneko@mech.t.u-tokyo.ac.jp).

M. Yoshizumi is with Hiroshima University Graduate School of Biomedical Sciences, Hiroshima 734-8551, Japan (e-mail: yos1956oktbh@hiroshima-u.ac.jp).

N. Suzuki is with the Department of Complementary and Alternative Medicine Clinical R&D, Kanazawa University Graduate School of Medical Science, Ishikawa 920-8640, Japan (e-mail: pcam@med.kanazawa-u.ac.jp).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TITB.2010.2091646

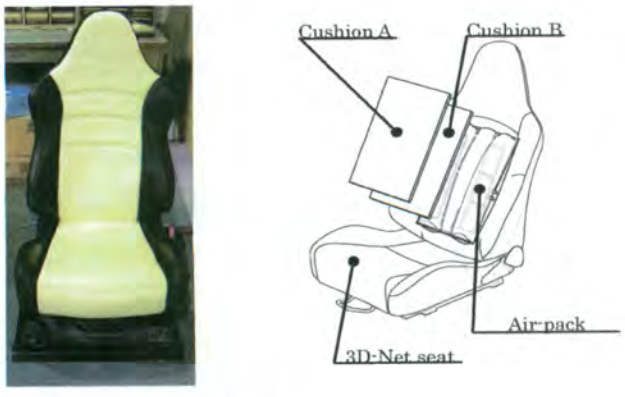

Fig. 1. Experimental apparatus.

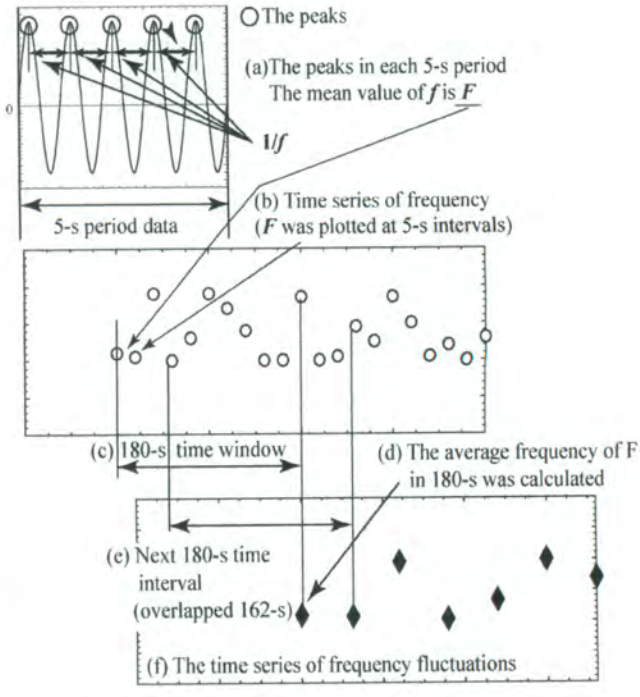

Fig. 2. Time series computation of frequency fluctuation.

body weight differences among the subjects were within 11% (mean weight: 55.0 kg).

All subjects underwent an ethanol patch test on the day prior to the experiment involving alcohol, and were verified to be of phenotype NN. Biological signals were taken from the subjects for 20 min prior to consuming alcohol, for subsequent comparison to signals from the noninvasive sensors in the air-pack. We recorded the biological data with 200 Hz. Subjects then consumed alcohol (beer, 500 ml) within 10 min, and the first measurements were taken during a 20-min period 20–40 min after consumption of the beer, when the blood alcohol is believed to reach the highest levels [11]. To observe the changes over time in all subjects, measurements were also recorded at 90–110 min and 160–180 min, for a total of four measurements. Subjects had not eaten for at least 3 h prior to consuming the alcohol, but were provided a typical volume of snacks along with the beer, to reproduce usual conditions under which alcohol is consumed. Otherwise, subjects consumed only water, no other food or drinks. The breath–alcohol concentration was measured before and after measuring all biological signals.

Then, all subjects participated in the aforementioned additional study on a different day. They underwent the same experiment without taking alcohol to highlight the biological signal differences between the normal and intoxicated states.

C. Analytical Method

The original waveforms from data strings of the digital pulse volume and the AP-PW from the first 5 min of measurements in each period for all subjects were compared using the spectral characteristics (FFT analysis) [12].

The analysis of the time series for frequency fluctuation of the AP-PW curves is shown in Fig. 2. Numbers (a)–(g), in Fig. 2, indicate methods used in the calculation. The AP-PW were filtered using frequency analysis to separate the signal of the body-trunk plethysmogram [13]. The Savitzky and Golay smoothing filter was used to find the maximum value in the time series of the AP-PW data [14]. (a) The peaks in each 5-s period of data were determined and the reciprocal of the time between peaks was evaluated to find the frequency f. Then, the mean value of f was calculated to find F. (b) F was plotted at 5-s intervals to create a time series of frequency. In order to identify long-term variations in the waveform of the time series. (c) A 180-s time window was defined. (d) The average frequency of F in 180 s was calculated and the frequency fluctuations were identified. (e) The same calculations were carried out for the next 180-s interval, which overlapped the previous interval by 162 s, and the results were plotted. (f) This process was repeated to create time series of frequency fluctuations.

Then, the digital pulse volume in the subjects was used to investigate the relationship between the consumption of alcohol and the nervous system. The heart rate variability (HRV) power spectrum was divided into high-frequency (HF: 0.15–0.40 Hz) and low-frequency (LF: 0.04–0.15 Hz) components. The HF component was used to infer parasympathetic nervous activity, whereas the LF/HF ratio of HR variability was defined as an indicator of sympathetic nerve activity. HF and LF were calculated by spectral analysis using the maximum entropy method (MEM) [15].

Finally, the mean value of the transitions of the dominant frequencies of the AP-PW in all subjects was derived from the 20 min of measurements in each period. The phenomenon of the AP-PW between the normal and intoxicated states was investigated for all subjects.

III. Results

Breath–alcohol concentration was measured before and after drinking (see Fig. 3). For all experiment subjects, the breath–alcohol concentration increased more than 0.1 mg/dl to an invigorated state.

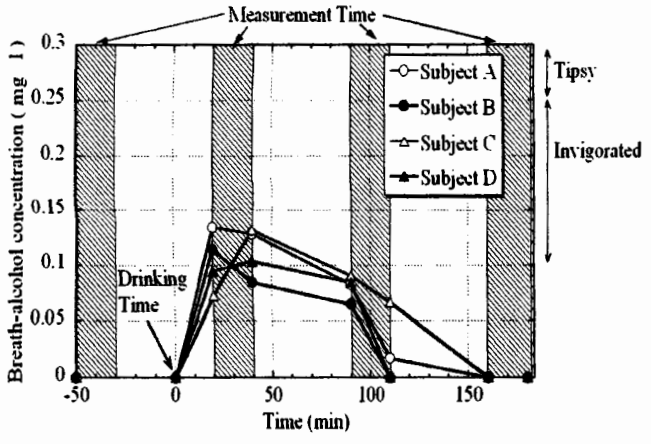

Fig. 3. Breath–alcohol concentration of the subjects.

The original waveforms from data strings of the digital pulse volume and the AP-PW from the first 5 min of measurements in all subjects are shown in Figs. 4 and 5. It seemed difficult to distinguish between the normal and intoxicated states based on these original biological signals.

The frequency analysis of the digital pulse volume and the AP-PW for the first 5 min of each measurement period with FFT analysis is shown in Fig. 6. As was seen in the frequency analysis, the frequency was influenced by the consumption of alcohol, showing a shift to higher frequencies.

The time series of frequency fluctuations of AP-PW in each measurement period are shown in Fig. 7. Then, the average value of the time series of frequency fluctuations of the AP-PW (AVE-AP-PW) in each measurement period of 20 min was calculated.

The changes in the breath–alcohol concentration and the AVE-AP-PW in each measurement period are shown in Fig. 8. The AVE-AP-PW decreased over time for all subjects under the nondrinking condition. However, the AVE-AP-PW increased and seemed to be returning to the zero level (Subjects A, B, and D) along with the breath–alcohol concentration, or only slightly decreased when compared to the nondrinking condition (Subject C).

The MEM analyses of HRV before and after the drinking are shown in Fig. 9. It seemed difficult to detect biological signals for the intoxicated condition with HRV analysis.

Then, the AVE-AP-PW in normal and intoxicated states are shown in Fig. 10. The level of AVE-AP-PW at the start of the first measurement of the experiment was adjusted to zero level. The AVE-AP-PW decreased at a relatively even rate in normal state, but the AVE-AP-PW gradually increased and then decreased in intoxicated state.

IV. Discussion

For all experiment subjects, the breath–alcohol concentration (see Fig. 3) increased more than 0.1 mg/dl to an invigorated state on the intoxicated scale [16]. Therefore, the amount of alcohol consumed was adequate to cause an intoxicated condition in the subjects. Also, according to the breath-concentration change in Fig. 3, it is considered that the subjects' body weight differences (up to 11%) and gender had limited affect on the degree of their intoxicated state.

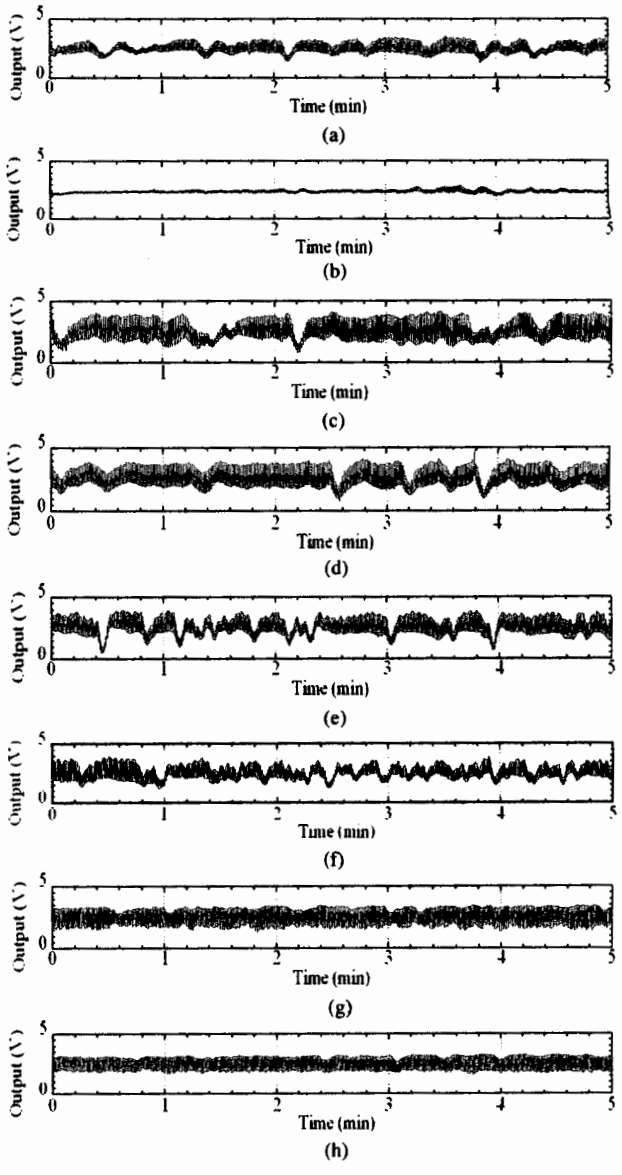

Fig. 4. Comparison of finger photoplethysmogram (before and after consuming alcohol). (a) Subject A (before consuming alcohol). (b) Subject A (after consuming alcohol). (c) Subject B (before consuming alcohol). (d) Subject B (after consuming alcohol). (e) Subject C (before consuming alcohol). (f) Subject C (after consuming alcohol). (g) Subject D (before consuming alcohol). (h) Subject D (after consuming alcohol).

In the frequency analysis of the digital pulse volume and the AP-PW with FFT analysis (see Fig. 6), the peaks of the frequencies of the digital pulse volume and of the AP-PW are nearly identical, indicating that the digital pulse volume is replaceable by the AP-PW [6] for noninvasive monitoring of the drivers.

Analyses of HRV before and after drinking with MEM are shown in Fig. 9. The sympathetic nervous system should be elevated by consuming alcohol [16]; therefore, the phenomenon of

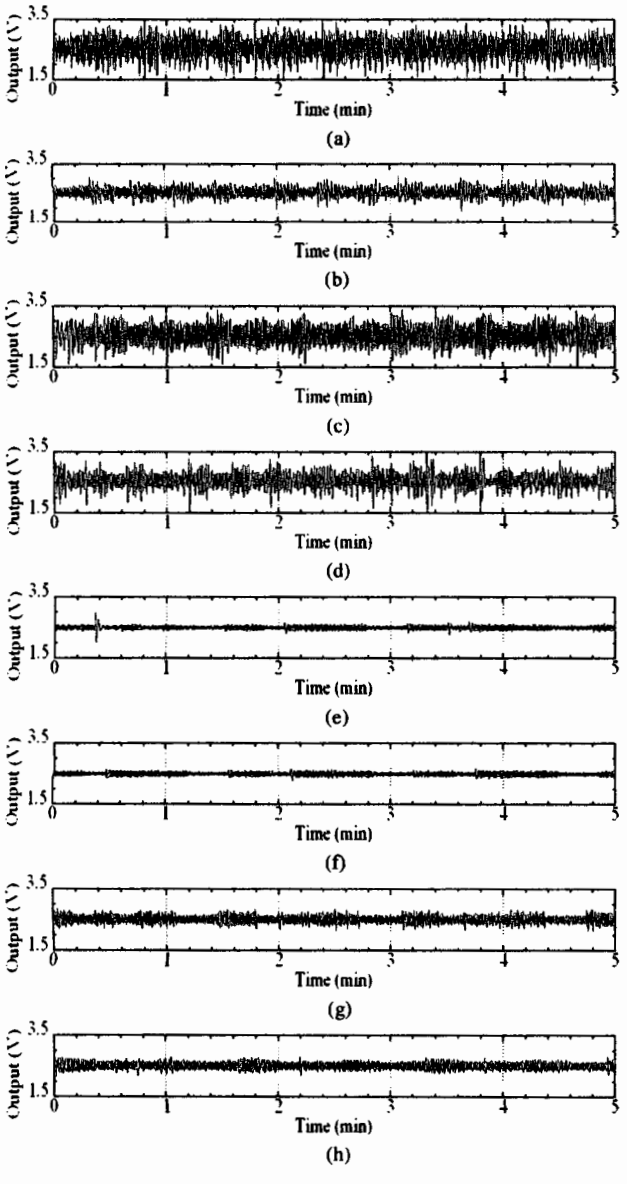

Fig. 5. Comparison of AP-PW (before and after consuming alcohol). (a) Subject A (before consuming alcohol). (b) Subject A (after consuming alcohol). (c) Subject B (before consuming alcohol). (d) Subject B (after consuming alcohol). (e) Subject C (before consuming alcohol). (f) Subject C (after consuming alcohol). (g) Subject D (before consuming alcohol). (h) Subject D (after consuming alcohol).

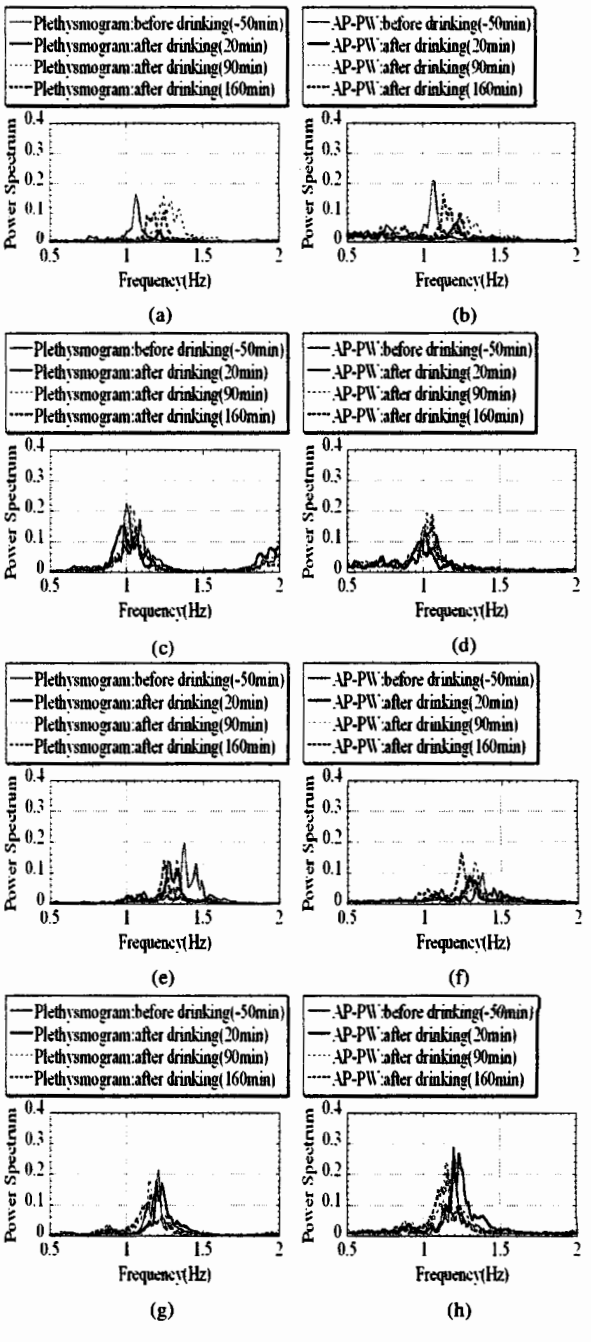

Fig. 6. FFT analysis of spectrogram of photoplethysmogram and AP-PW in the first 5 min for the subjects. (a) Subject A (photoplethysmogram). (b) Subject A (AP-PW). (c) Subject B (photoplethysmogram). (d) Subject B (AP-PW). (e) Subject C (photoplethysmogram). (f) Subject C (AP-PW). (g) Subject D (photoplethysmogram). (h) Subject D (AP-PW).

an increase in the level of LF/HF and a decrease in HF should be observed. But, HRV did not indicate a specific change in all the subjects. HRV analysis might have captured the subjects' stress from the long-time sitting on the seat during the experiment as well as the intoxicated condition under the influence of alcohol. It seemed difficult to detect biological signals for the intoxicated condition with only HRV analysis.

Characteristics of the AVE-AP-PW in normal and intoxicated states were different. The AVE-AP-PW decreased at a relatively even rate in normal state, but the AVE-AP-PW gradually increased and then decreased in intoxicated state (see Fig. 10). The increase of nonlinear behavior of the AVE-AP-PW under the influence of alcohol was suspected. All subjects under this condition were affected by external factors such as sitting a long time on the seat. It could be possible to use the behavior of the AVE-AP-PW to distinguish between a person's normal and intoxicated state by detecting nonlinear behavior of the AVE-AP-PW. Our results showed that it might be possible to detect an intoxicated state using the AVE-AP-PW. However, we also

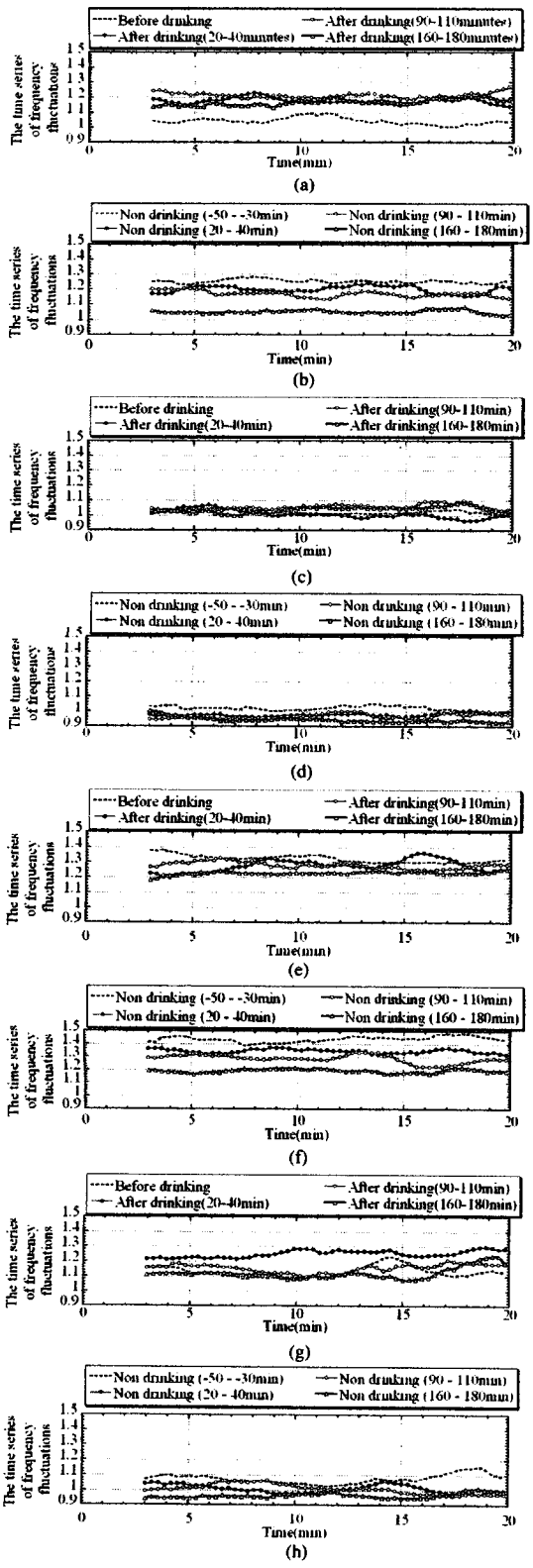

Fig. 7. Time series of frequency fluctuations of AP-PW in each measurement period. (a)Time series of frequency fluctuations (Subject A: drinking). (b) Time series of frequency fluctuations (Subject A: nondrinking). (c) Time series of frequency fluctuations (Subject B: drinking). (d) Time series of frequency fluctuations (Subject B: nondrinking). (e) Time series of frequency fluctuations (Subject C: drinking). (f) Time series of frequency fluctuations (Subject C: nondrinking). (g) Time series of frequency fluctuations (Subject D: drinking). (h) Time series of frequency fluctuations (Subject D: nondrinking).

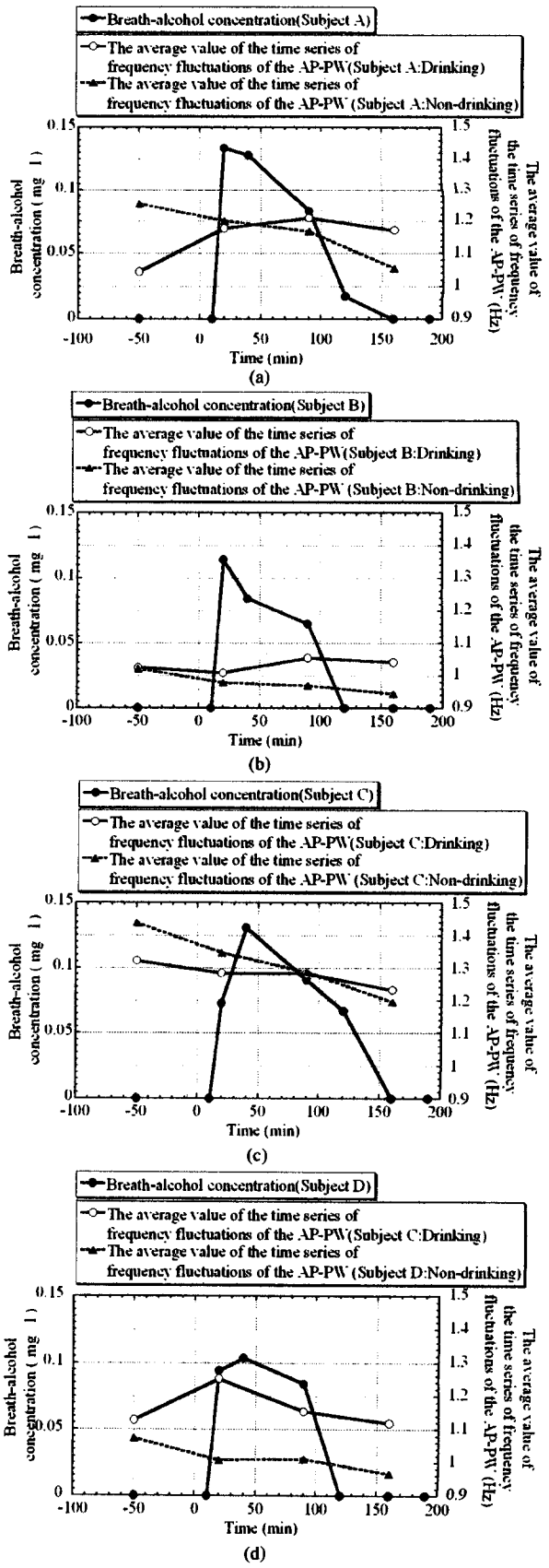

Fig. 8. Average value of the time series of frequency fluctuations of the AP-PW in each measurement period. (a) Subject A. (b) Subject B. (c) Subject C. (d) Subject D.

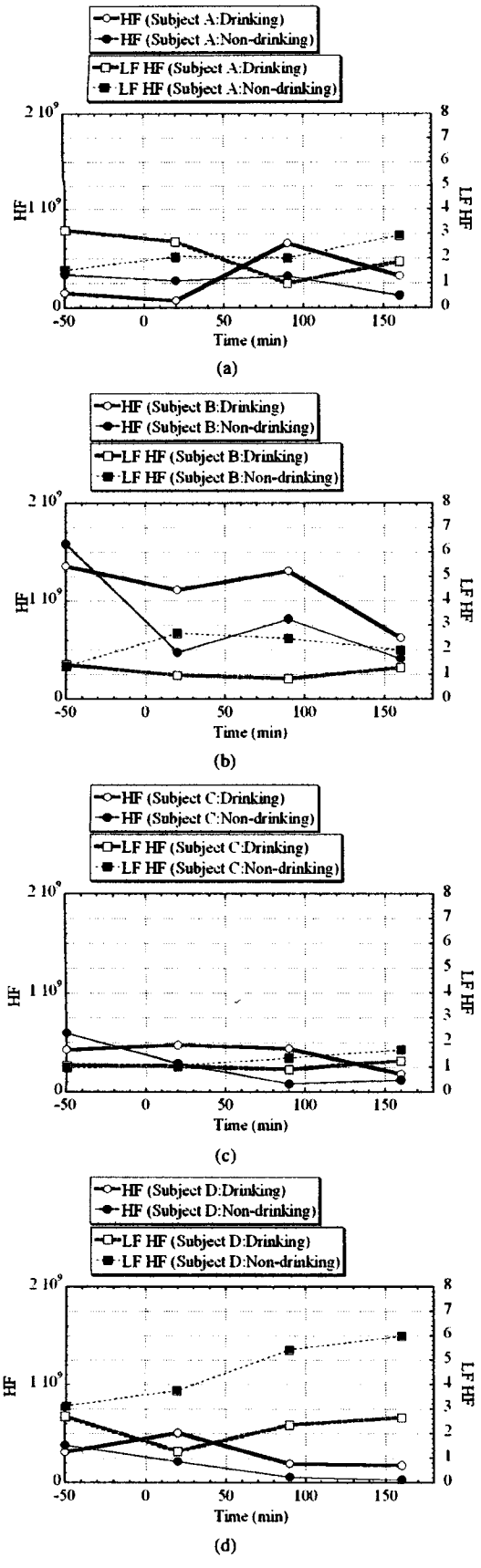

Fig. 9. MEM analysis of HRV. (a) Subject A. (b) Subject B. (c) Subject C. (d) Subject D.

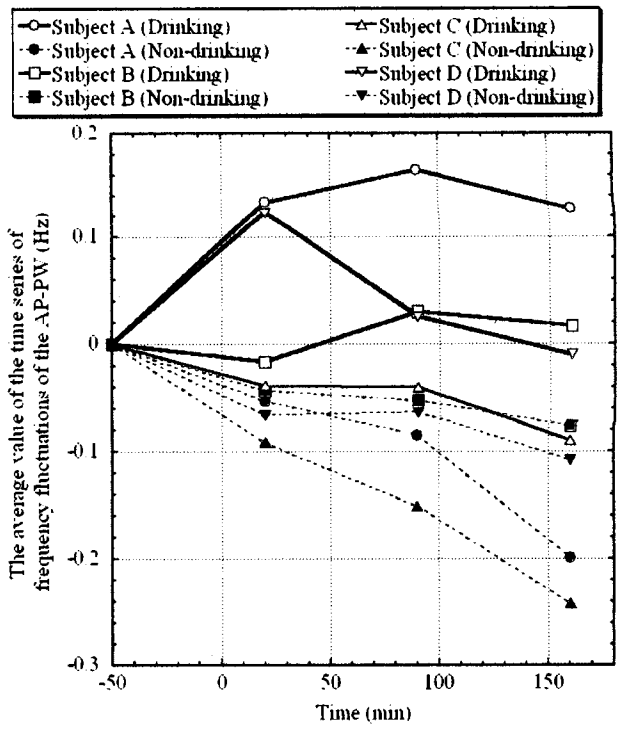

Fig. 10. AVE-AP-PW in normal and intoxicated states.

found that it was not possible to detect an intoxicated state using HRV analysis with MEM.

Compared to previous studies monitoring the condition of the driver, our approach using the AVE-AP-PW has the advantage to capture the drivers' biological signals by noninvasive methods without any electrical devices on the body during driving. And its techniques for filtering noise or artifact signals are not complicated compared to those of an EEG [1]–[3]. It is not necessary to add other signals such as eye movement or eye blinks to increase the reliability of our algorithm with AVE-AP-PW to distinguish between normal and intoxicated states [2], [3]. Also, it is not necessary for the drivers to do any task to measure performance [4].

This study has several limitations. First, the method using the AVE-AP-PW could not distinguish between a person's normal and intoxicated state without baseline data of a nondrinking state. It is necessary to consider a way to quantify nonlinearity of the AVE-AP-PW before and after drinking. Second, a long-time measurement would be needed for using AVE-AP-PW to distinguish a normal and an intoxicated state, when comparing to the breath–alcohol concentration measurement. It is necessary to minimize the measurement time. Third, regarding the external factors, further research in real-environment conditions is still needed to enhance this system for detecting drunk driving. Finally, the findings concerning the relationship between the nonlinearity of the AVE-AP-PW under the influence of alcohol and the breath–alcohol concentration is preliminary, and the strength of our conclusions is limited by the small number of subjects. Therefore,

further research with more subjects is needed to confirm our findings.

V. Conclusion

An air-pack sensor installed in an automobile seat was found to record the same pulse wave, a pulse frequency peak as the signal provided by a digital pulse volume probe. Measurements of the AP-PW for 20 min also revealed differences due to the consumption of alcohol, suggesting that the AP-PW contains potential information to distinguish sobriety from intoxication. The algorithm for the time series of the frequency fluctuations generated in this study has this potential.

References

[1] C. Papadelis, C. Kourtidou-Papadeli, P. D. Bamidis, I. Chouvarda, D. Koufogiannis, E. Bekiaris, and N. Maglaveras, "Indicators of sleepiness in an ambulatory EEG study of night driving," in *Proc. IEEE Eng. Med. Biol. Soc. Conf*, 2006, vol. 1, pp. 6201–6204.

[2] C. Papadelis, Z. Chen, C. Kourtidou-Papadeli, P. D. Bamidis, I. Chouvarda, E. Bekiaris, and N. Maglaveras, "Monitoring sleepiness with on-board electrophysiological recordings for preventing sleep-deprived traffic accidents," *Clin. Neuro. Physiol.*, vol. 118, pp. 1906–1922, 2007.

[3] A. Picot, S. Charbonnier, and A. Caplier, "On-line automatic detection of driver drowsiness using a single electroencephalographic channel," in *Proc. IEEE Eng. Med. Biol. Soc. Conf.*, 2008, pp. 3864–3867.

[4] E. J. Ogden and H. Moskowitz, "Effects of alcohol and other drugs on driver performance," *Traffic Inj. Prev.*, vol. 5, pp. 185–198, 2004.

[5] International Council on Alcohol, Drugs and Traffic Safety (ICADTS) Working Group on Alcohol Ignition Interlocks. (2001, Jul.). "Alcohol ignition interlock devices. Volume I: Position paper."

[6] S. Kojima, K. Murata, E. Fujita, S. Maeda, Y. Ogura, T. Kamei, T. Tsuji, R. Miyoshi, and S. Kaneko, "Development of air-pressure sensor with the built-in seat," in *Proc. 23rd Symp. Biol. Physiol. Eng.*, 2008, pp. 239–242.

[7] S. Kojima, S. Maeda, Y. Ogura, E. Fujita, K. Murata, T. Kamei, and S. Kaneko, "The method for drinking detection by biological signals," in *Proc. Dynamics Des. Conf.*, 2008 [CD-ROM].

[8] S. Kojima, S. Maeda, Y. Ogura, E. Fujita, K. Murata, T. Kamei, T. Tsuji, Y. Ueno, and S. Kaneko, "The Method for non-aggression biological signal sensing system of drinking detection," in *Proc. 41st Japan Ergonom. Soc. Chugoku and Shikoku Branch*, 2008, pp. 60–61.

[9] E. Fujita, Y. Ogura, N. Ochiai, T. MIAO, T. Shimizu, T. Kamei, K. Murata, Y. Ueno, and S. Kaneko, "Development of the measurement method of the prediction of sleep by finger plethysmogram data," *Jpn. J. Ergonom.*, vol. 41, pp. 203–212, 2005.

[10] A. Imanishi and M. Okaya-Higa, "Relations between the different parameters of chaos analysis and largest lyapunov exponent in finger plethysmograms," *Jpn. J. Ergonom.*, vol. 45, no. 2, pp. 141–147, 2009.

[11] K. Ameno, H. Kinoshita, S. Ameno, and I. Ijiri, "Gastrointestinal absorption of ethanol," *Nippon Rinsho*, vol. 55, pp. 11–15, 1997.

[12] J. S. Bendat and A. G. Piersol, "Random data," in *Analysis and Measurement Procedures*. California, LA, Wiley, 1971, pp. 298–304 (Japanese translation).

[13] S. Maeda, E. Fujita, Y. Ogura, and S. Kaneko, "A research on sensing method of biological signals from the hips," in *Proc. JSME Annu. Meeting*, 2006, vol. 2006-5, pp. 79–80.

[14] A. Savitzky and M. J. E. Golay, "Smoothing and differentiation of data by simplified least squares procedures," *Anal. Chem.*, vol. 36, pp. 1627–1639, 1964.

[15] Y. Ishikawa, *Wavelet Analysis for Clinical Medicine*. Tokyo, Japan: Igakushoin, 2000, pp. 310–329.

[16] K. Hirayanagi, N. Yamaguchi, and T. Shiozawa, "Effects of fixed alcohol concentrations in expiration on task performance," *Jpn. J. Ergonom.*, vol. 42, pp. 337–342, 2006.

Authors' photographs and biographies not available at the time of publication.