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Non-contact Unconstrained Continuous Pulse Wave Measurement during Long-distance Truck Operation

Emi YUDA[1] and Junichiro HAYANO[2]

[1] Center for Data-driven Science and Artificial Intelligence, Tohoku University, 41 Kawauchi, Aoba-ku, Sendai, 980-8576, Japan
emi.a.yuda@tohoku.ac.jp
[2] Representative director and CEO, Heart Beat Science Lab, Co., Ltd., 6-6-40 Aza Aoba, Aramaki, Aoba-ku, Sendai, 980-0845, Japan
hayano@acm.org

Abstract. To examine the possibility of non-contact unconstrained continuous pulse wave measurement during driving, we installed a microwave Doppler element pulse wave sensor on the dashboard of a large truck. The sensor detects the pulsatile movements of the heart and blood vessels from the Doppler shift of the reflected waves of microwaves emitted toward a person at a distance. We analyzed pulse rate variability from the signal during a long-distance operation and compared it with heart rate variability obtained from ambulatory electrocardiogram recorded simultaneously.

Keywords. Pulse wave, non-contact sensing, unconstrained measurement, heart rate variability, driving

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1 Introduction

The detection of drowsiness of drivers is an essential element for preventing traffic accidents. For this purpose, several studies suggested the usefulness of heart rate variability analysis during driving. Awais et al. [1] reported a method combining heart rate variability metrics from electrocardiogram and time and frequency domain metrics from electroencephalogram. Using support vector machine (SVM) with these metrics, they developed a model discriminating between alert and drowsy states with 80% accuracy. Buendia et al. [2] and Forcolin et al. [3] proposed methods to remove outlier heartbeat data to improve the drivers' drowsiness detection by heart rate variability. They reported the importance of preprocessing of heartbeat signals.

In the vital sign monitor during driving, unconstrained is an important factor for practical application. Even if the usefulness of the heart rate variability analysis to detect drivers' drowsiness is established, it is necessary to have a reliable heartbeat signal during driving. However, it is difficult for drivers to wear an electrocardiogram electrode every time they drive. Therefore, it is ideal if there is a means by which the driver does not have to install the device and can monitor it without awareness. In this study, we aimed at examining the usefulness of a microwave Doppler element pulse wave sensor for non-contact unconstrained continuous pulse wave measurement during driving. This sensor emits microwaves toward a person at a distance and detects the pulsatile movements of the heart and blood vessels from the Doppler shift of reflected microwave frequency using an ultra-high frequency resolution analysis method called non-harmonic analysis [4].

2 Experiments

2.1 Sensor

We examined a microwave Doppler element sensor (CRA-X, Calea Corporation, Toyama, Japan) (Fig. 1). Although the detailed technology of the sensor is not published, the sensor is commercially available. Since the sensor needs to detect the Doppler frequency shift of reflected microwave caused by fine pulsatile movements of the heart and blood vessels, the key technology is the high-resolution frequency analysis of noisy signals. The sensor used a non-harmonic analysis [4,5] for this purpose. For frequency analyses such as discrete Fourier transform, there is generally a trade-off between frequency and time resolution. If the frequency resolution is low, the noise spectra can overlap with those of signals.

Similarly, if the time resolution is low, rapid frequency variations cannot be detected. The non-harmonic analysis is known to prove a high accuracy for detached frequency components with only slight effects of the frame length, yielding an approximately 2 dB improvement in signal-to-noise ratio compared with discrete Fourier transform [4]. Konishi et al. [6] reported that the microwave Doppler sensor incorporating this technology could be embedded in the backrest of a vehicle seat to detect the driver's heartbeat. Their research, however, was only performed in steady-state using a virtual reality driving simulator, not during actual driving. We, therefore, performed the present study to examine the usefulness of this device during actual driving.

Fig. 1 Microwave Doppler sensor (Calea Corporation, Toyama, Japan)

In the present study, the device was mounted on the dashboard of a heavy truck so that the sensor turned to the middle of the driver's chest. The pulse wave signal was processed in real-time by dedicated software in the device, and the secondary information was transferred to the cloud server (AWS, Amazon Web Services, USA). As a reference signal, an ambulatory electrocardiogram (ECG) was simultaneously recorded. Three electrodes for the NASA and CM5 leads and a micro ECG recorder (Cardy 303 pico+, Suzuken, Co., Ltd., Nagoya, Japan) were attached to the chest wall. The digitized ECG signal was recorded continuously and stored in the recorder.

2.2 Protocol.

The experiment was performed on a healthy male truck driver (47 y old). Pulse waves and ECG were continuously recorded during a long-haul truck operation between Komaki City and Morioka City, Japan. He left Komaki at 15:07 and arrived at Morioka at 05:07 the next day, during which he took the first naps at 00:05 in the highway service area. The pulse wave signal from the microwave Doppler element sensor was recorded continuously but only when he sat in the driver's seat.

2.3 Data analysis.

The pulse wave signals from the microwave Doppler element sensor were analyzed by dedicated software provided by Calea Corporation (Toyama, Japan) and output as time-series data of instantaneous pulse rate (PR) every one second. The time-series data were converted into instantaneous pulse interval time series data every second.

ECG signal was analyzed by a Holter ECG scanner (Cardy Analyzer 5, Suzuken, CO., Ltd., Nagoya, Japan), by which all QRS-waves were detected and labeled for the types of cardiac rhythm. R-R interval time series were generated only using consecutive QRS-waves with sinus rhythm. The time series were interpolated with a step function, resampled at 1 Hz, yielding instantaneous R-R interval time series at every one second. The relationship between the instantaneous pulse intervals and R-R intervals was analyzed by cross-spectral analysis, which provided the coherence and transfer phase between the two signals.

The time-series data of pulse intervals and R-R intervals wave were also analyzed for heart rate variability (HRV) by the method of complex demodulation [7]. Complex demodulation demodulates the amplitude and frequency of frequency components within a given frequency band as the continuous functions of time. In this study, the amplitude of very-low frequency (VLF, 0.0033-0.04 Hz), low frequency (LF, 0.04-0.15 Hz), and high frequency (HF, 0.15-0.40 Hz) component were demodulated continuously and averaged every minute. The frequency was demodulated only for the HF component to estimate respiration frequency. Additionally, minute-to-minute PR and heart rate (HR) were calculated from the 1-minute segmental means of the second-to-second pulse intervals and R-R intervals, respectively.

2.4 Statistical analysis.

The program package of the Statistical Analysis System (SAS Institute, Cary, NC, USA) was used for statistical analysis. Correlations between metrics obtained from pulse interval and R-R interval were evaluated by product-moment correlation coefficients using the Correlation procedure. The agreement between PR and HR was evaluated by Bland and Altman plot and the degree of agreement [8]. $P < 0.05$ was used as the criterion for statistical significance.

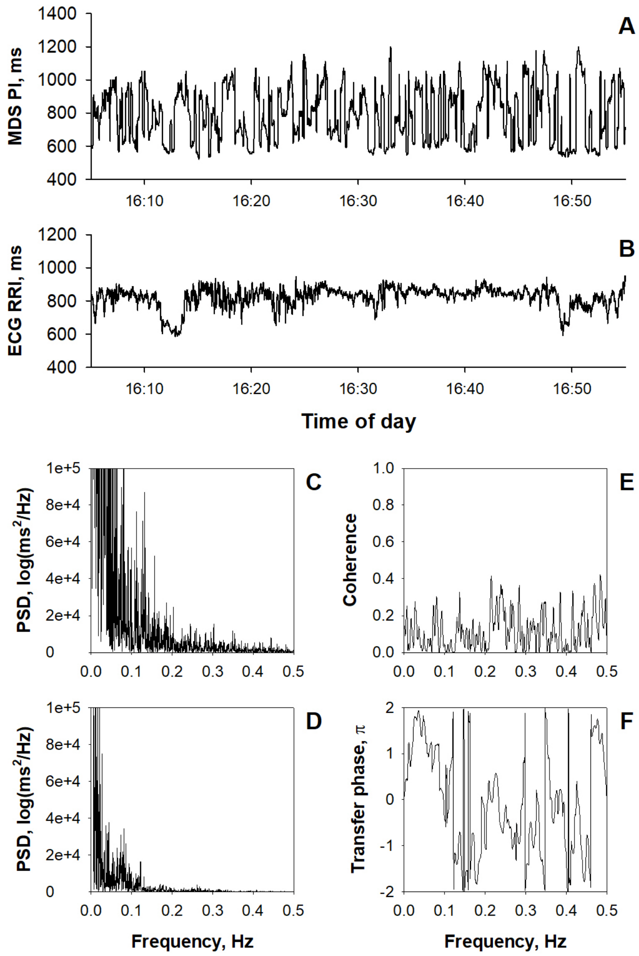

Fig. 2 Cross-spectral analysis between instantaneous pulse intervals (PI) measured by microwave Doppler sensor (panel A) and instantaneous R-R intervals (RRI) of ECG (panel B). Panels C and D present power spectra of PI and RRI, respectively. Panel E shows the coherence (not squared) between them and panel F shows the transfer phase form RRI to PI. PSD = power spectral density.

3 Results

Fig. 2 shows the results of cross-spectral analysis between instantaneous pulse intervals obtained from the microwave Doppler sensor and R-R intervals of ECG recorded simultaneously. Although these data were extracted from the 50-min period when the most stable pulse interval signal was obtained during driving, the pulse interval signal contained a lot of noise. Additionally, although it is not clear from this figure, about 8% of the microwave Doppler element sensor signal was missing due to communication failure. As expected, the power spectra of the two signals differed apparently (Fig 2 panels C and D), and the coherence (Fig 2 panel E) was <0.4 for all frequency bands where R-R intervals showed a power spectral density ≥8 ms2/Hz (the minimum detectable fluctuation estimated from the sampling frequency of ECG, 125 Hz).

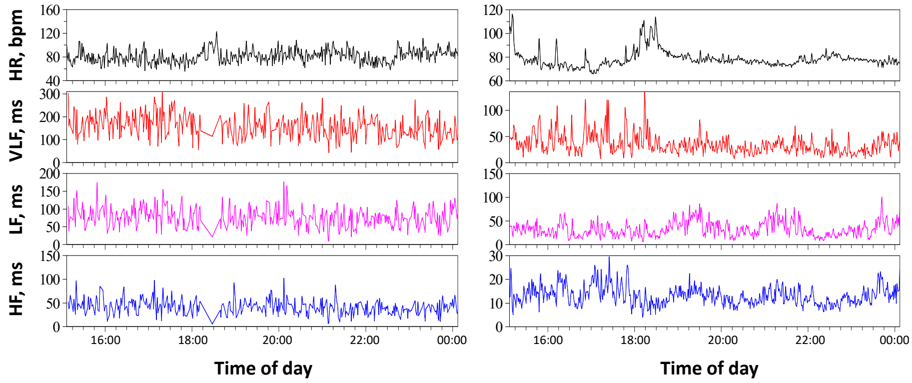

Fig. 3 Heart rare (HR) and the amplitude of frequency components of heart rate variability (HRV) calculated from pulse interval (left panel) and R-R interval (right panel) during 9 h after the start of driving. The amplitude of each HRV frequency component was calculated by complex demodulation as continuous functions of time and averaged over every one min.
LF = low frequency (0.04-0.15 Hz) component, HF = high frequency (0.15-0.4 Hz) component, VLF = very-low-frequency (0.0033-0.04 Hz) component.

Fig. 3 presents the results of HRV analysis from microwave Doppler sensor pulse interval and ECG R-R interval. Fig 4 shows the relationships between minute-to-minute PR and HR and between minute-to-minute HRV metrics obtained from pulse interval and R-R interval. For these analyses, a significant yet weak positive correlation was observed between PR and HR and the Bland and Altman plot showed the degree of agreement from -24 to 27 bpm. No significant correlation was observed for LF or VLF amplitude or HF frequency. A significant correlation was observed only for HF amplitude but was a negative correlation.

4 Discussion

To examine the possibility of non-contact unconstrained continuous pulse wave measurement during driving, we installed a microwave Doppler element pulse wave sensor on the dashboard of a large truck. Using continuous signals recorded during a long-distance truck operation, we compared the pulse intervals obtained from the microwave Doppler element sensor, the instantaneous R-R intervals obtained from ECG recorded simultaneously, and HRV indices calculated from both signals. In the signal obtained from the microwave Doppler sensor, data loss of about 8%, which is considered to be caused by a communication failure, was observed. Also, the pulse interval signal contained a lot of noise. As a result, the coherence between the pulse intervals and R-R intervals was low (<0.4) for all frequency bands where the minimum level of R-R interval fluctuations. Also, HRV analysis on the pulse interval signal showed no agreement with the result obtained from ECG R-R intervals recorded simultaneously.

Because the present result is based on one measurement data of one case, no definitive conclusion can be obtained; but the microwave Doppler element sensor installed on the dashboard of a large truck does not provide reliable estimates of PR, at least during actual driving. In particular, it was observed that not only did the instantaneous pulse interval not match the instantaneous R-R interval, but the 1-min average PR did not match the 1-min average HR of the ECG. Analysis of pulse variability has been recognized to provide only a limited surrogate for R-R interval HRV due to the confounding effects of various physiological variability other than HRV on pulse variability [9]. However, even studies that report discrepancies between pulse rate variability and ECG HRV report that mean PR and mean HR is at least consistent [10-15]. Nevertheless, we did not observe any agreement even between them. In order to use the instantaneous pulse intervals obtained from the microwave Doppler element sensor as a surrogate of R-R interval and as the source signal for HRV analysis during driving, further improvements are required for reducing communication failure and noise.

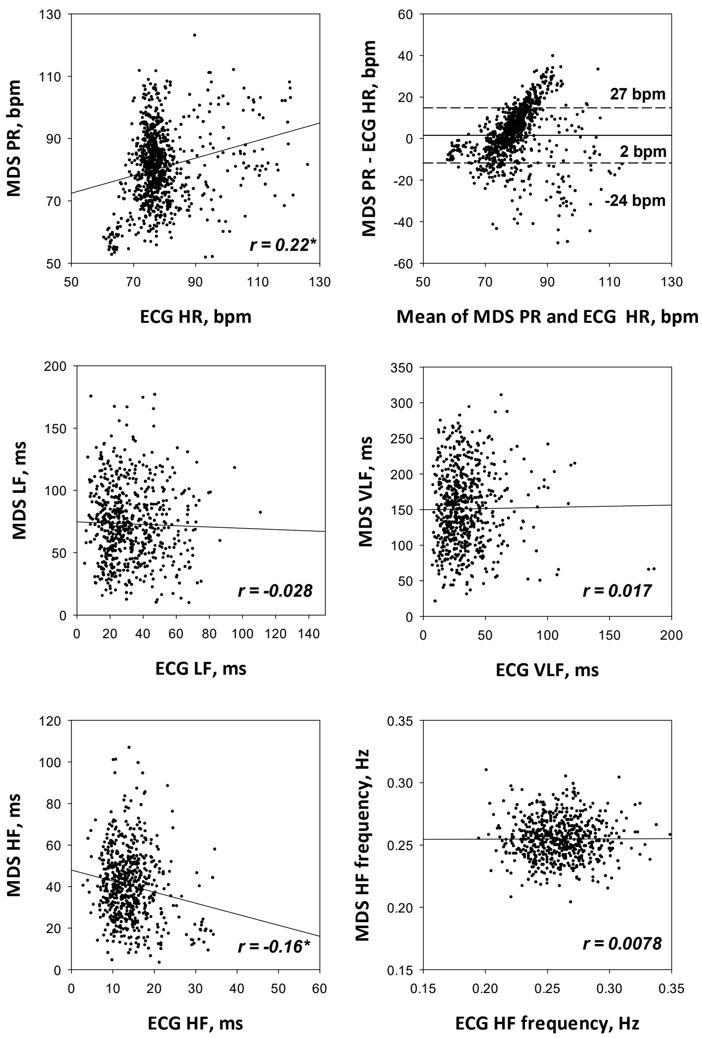

Fig. 4 Relationship between metrics calculated from microwave Doppler sensor (MDS) pulse interval and ECG R-R interval. In all panels, each data point represents an (x, y) pair of 1-min average values of respective metrics during 9h after the start of driving. All panels but one at the

upper-right corner show correlations with a linear regression line and correlation coefficients (*r*, * indicates statistically significant *r*). The panel at the upper-right corner is a Bland and Altman plot for pulse rate (PR) and heart rate (HR), in which solid horizontal line shows the average of difference and horizontal dashed lines present the degree of agreement (± 1.92 SD). HF = high frequency (0.15-0.4 Hz), LF = low frequency (.04-0.15 Hz), VLF = very low frequency (0.0033-0.04 Hz) components.

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Name:
Emi YUDA

Affiliation:
Assistant Professor, DEng, PhD., Center for Data-driven Science and Artificial Intelligence, Tohoku University

Brief Biographical History:
2013- Research Assistant, Dept. of Computer Science, Santa Monica College
2015- NEDO Project Researcher, Dept. of Medical Sciences, Nagoya City University
2019 PhD, Nihon University
2019- Assistant Professor, Dept. of Engineering, Tohoku University
2020 DEng, Niigata University
2020- Assistant Professor, Center for Data-driven Science and Artificial Intelligence, Tohoku University

Membership in Academic Societies:

- The Institute of Electrical and Electronics Engineers (IEEE)
- The Information Processing Society of Japan (IPSJ)
- The Society of Automotive Engineers of Japan (JSAE)

Name:
Junichiro HAYANO

Affiliation:
Representative Director and CEO, Heart Beat Science Lab, Co., Ltd.; Honored Professor, MD, PhD., Nagoya City University

Brief Biographical History:
1980 MD, Nagoya City University
1983 Research Fellow, Psychosomatic Medicine, Kyushu University
1988 PhD, Nagoya City University Graduate School of Medical Sciences
1990 Visiting Associate, Behavioral Medicine Research Center, Duke University Medical Center, Durham, NC, USA
1992 Assistant Professor, Nagoya City University Medical School
1999 Associate Professor of Medicine, Nagoya City University Graduate School of Medical Sciences
1999 Director of Psychosomatic Medicine, Nagoya City University Hospital
2003 Vice Director of the Center for Graduate Medical Education Research and Development, Nagoya City University Hospital
2007 Professor, Nagoya City University Graduate School of Medical Sciences
2020 Representative director and CEO, Heart Beat Science Lab, Co., Ltd.
2021 Honored Professor, Nagoya City University

Membership in Academic Societies:

- The Japanese Society of Physiological Anthropology
- The Japanese Society of Medical and Biological Engineering