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Design and Evaluation of Digital Filters for Non-Contact Measuring of HRV using Medical Radar and Its Application in Bedside Patient Monitoring System

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***Abstract*—A non-contact bedside monitoring system using medical radar is expected to be applied to clinical fields. Our previous studies have developed a monitoring system based on medical radar for measuring respiratory rate (RR) and heart rate (HR). Heart rate variability (HRV), which is essentially implemented in advanced monitoring system, such as prognosis prediction, is a more challenging biological information than the RR and HR. In this study, we designed a HRV measurement filter and proposed a method to evaluate the optimal cardiac signal extraction filter for HRV measurement. Because the cardiac component in the radar signal is much smaller than the respiratory component, it is necessary to extract the cardiac element from the radar output signal using digital filters. It depends on the characteristics of the filter whether the HRV information is kept in the extracted cardiac signal or not. A cardiac signal extraction filter that is not distorted in the time domain and does not miss the cardiac component must be adopted. Therefore, we focused on evaluating the interval between the R-peak of the electrocardiogram (ECG) and the radar-cardio peak of the cardiac signal measured by radar (R-radar interval). This is based on the fact that the time between heart depolarization and ventricular contraction is measured as the R-radar interval. A band-pass filter (BPF) with several bandwidths and a nonlinear filter, locally projective adaptive signal separation (LoPASS), were analyzed and compared. The optimal filter was quantitatively evaluated by analyzing the distribution and standard deviation of the R-radar intervals. The performance of this monitoring system was evaluated in elderly patient at the Yokohama Hospital, Japan.**

I. INTRODUCTION

Vital signs, which are an objective index of health status, are important to monitor through continuous measurement [1]. Moreover, contact measurement is not suitable for long-term measurement because of the physical burden of placing electrodes on the skin. In this regard, a non-contact technology using radar is expected [2]. We have proposed a RR and HR monitoring system for the elderly inpatient, and have shown the possibility of predicting the onset of pneumonia [3, 4]. In addition, HRV is a vital sign that is more informative than the RR and HR, as it shows the fluctuation of the time interval between heartbeats owing to the influence of the autonomic nervous system. Because a decrease in HRV is closely related to cardiac diseases, such as myocardial infarction, it is expected to be applicable to prognosis prediction [5, 6].

A non-contact HRV measurement using a radar is challenging because the cardiac component in the radar output signal is smaller than the respiratory element by a factor of 10 to 100 [7]. Figure 1 shows a system configuration for measuring HRV with a radar. It is necessary to extract the detailed cardiac component from the radar output signal using a filter. In addition, to contain the HRV information in the extracted cardiac signal, a filter must satisfy the two following conditions. First, the extracted cardiac signal must not miss the radar-cardio peaks. Second, the extracted cardiac signal must not be distorted in the time domain because the deviation of the peak interval owing to distortion will cause errors in the HRV measurement.

A BPF, which is the most common method, is used to extract the cardiac component [8, 9]. This is based on the fact that the frequency band of the cardiac component is 1–3 Hz [10, 11]. While BPF is a simple method, there are concerns about signal distortion. LoPASS is adopted for cardiac signal extraction, which is a nonlinear filtering method that uses geometric projection in delay space [12, 13]. It has been shown to correlate with heartbeats and radar-cardio peaks. However, the applicability to HRV measurement has not yet been investigated.

In this study, we propose evaluation methods based on the interval between the R-peak of the ECG and the cardiac peak extracted from the radar to investigate the best cardiac signal extraction method for the HRV measurement, which overcomes the problems of missing the cardiac peak in the radar output signal and the distortion of the cardiac signal. To the best of our knowledge, no well-considered research has been shared on the physiological time interval between the electrical activity caused by cardiac depolarization and the mechanical activity caused by ventricular contraction. The distortion of the cardiac extraction filter was evaluated visually and quantitatively by analyzing the R-radar intervals.

The remainder of this paper is organized as follows. Three BPF and LoPASS filter are analyzed and compared mathematically and experimentally in Section II. Section III presents the results of the two methods. Finally, the most suitable filter for the HRV measurement is provided in the conclusion and discussed in Section IV. The data used to

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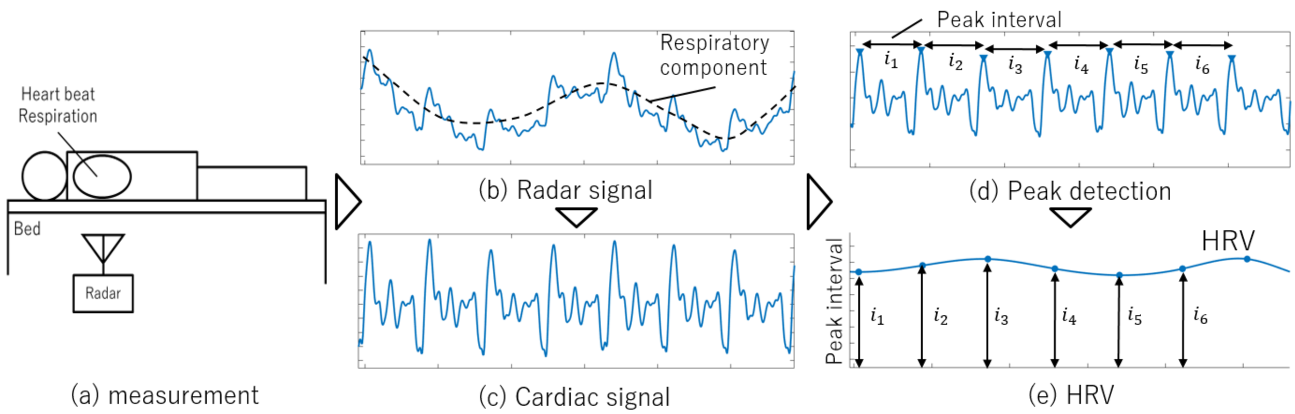

Figure 1. Configuration for a non-contact measurement to HRV estimation using Doppler radar: (a) Doppler radar is used, (b) Respiratory and cardiac components are captured as the radar signal, (c) Extracted cardiac signal filter is used to extract the cardiac signal from the radar signal., (d) The peak of the cardiac signal is detected, and the peak-to-peak interval is calculated, (e) HRV is described by converting the peak interval to the y-axis.

demonstrate clinical applicability in this study were obtained from elderly patient at Yokohama Hospital in Japan.

II. Materials and Methods

A. Hardware configuration for HRV filter evaluation

The system includes a 24 GHz Doppler radar (New Japan Radio, NJR4262) and an ECG (BIOPAC, BN-REPEC). The distance between the subject and the radar is 15 cm. The radar accepts the displacement of the chest wall owing to respiration and heartbeat as a received signal. The received signal is mixed with the transmitted signal, and the outputs I and Q signals are presented as Eqs. (1) and (2), where $x(t)$ denotes the displacement of the chest wall, λ denotes the wavelength, and ϕ denotes the total residual phase accumulated in the circuit along the transmission path [14].

$$I(t) = cos\left(\frac{4\pi x(t)}{\lambda} + \phi\right) \quad (1)$$

$$Q(t) = sin\left(\frac{4\pi x(t)}{\lambda} + \phi\right) \quad (2)$$

In the heart, the electrical signal generated by depolarization causes the ventricles to contract through the myocardium, thereby supplying blood to the entire body. The transmission time from depolarization to contraction is constant, although it varies from person to person. Here, the ECG records the electrical signals flowing through the heart, and the radar records the displacement of the chest wall as the ventricles contract [15]. Because of these physiological characteristics, the R-radar interval between the electrical and mechanical heartbeat signals of the heart is always constant.

The radar and ECG signals were synchronized and recorded using an analog-to-digital converter at a sampling rate of 1000 Hz, and then the radar signal was down-sampled to 100 Hz. The signals were recorded using the LabVIEW software (National Instruments, USA) and analyzed using MATLAB (MathWorks, USA).

B. BPF configuration and LoPASS theory

A fifth-order linear Butterworth filter was used as the BPF with three cutoff frequencies of 0.75–5 Hz, 0.75–10 Hz, and 0.75–20 Hz because there is a relationship between the bandwidth and the distortion of the filtered signal.

The cardiac extraction algorithm LoPASS is based on locally projective noise reduction (LPNR) [12], a nonlinear filtering technique that uses geometric projections in the delay space to achieve in-band noise reduction. LPNR was first proposed by [16] and has been applied to signal separation for ECG, ballistocardiogram (BCG) and radar [12, 13, 17]. In brief, LPNR rests on the assumption that future samples can be deterministically forecast from past samples.

$$x_{T+1} = f(x_T) \quad (3)$$

where x_t represents a delay vector including m samples up to time step t, and m is the embedding dimension.

$$x_t = (x_{t-m}, \dots, x_{t-1}, x_t)^T \quad (4)$$

Linearizing the function $f(\cdot)$ and encoding the fundamental dynamic that generates the signal, one obtains an approximate value, at the current position x_0, for the manifold in the delay space occupied by the deterministic signal

$$x_{T+1} = x_0 + A(x_T - x_0) \quad (5)$$

Because the manifold is aggregated into a lower-dimensional subspace, matrix A will encode the dimensions in which the signal expands around x_0. Thus, the noise components occupy the perpendicular to matrix A, and to reduce noise, it is projected onto the subspace extended by the columns of A.

C. R-radar interval evaluation and procedure

The most suitable filter for the HRV measurement was evaluated by comparing the ECG R-peak with the radar-cardio peak filtered from the radar signal. Figure 2 (a) presents the procedure for calculating the R-radar interval from the ECG and radar signals. The ECG signal was pre-processed with a low-pass filter at 30 Hz, and the R-peak was detected using the Pan–Tompkins algorithm [18]. The cardiac signal extracted from the radar was detected using the "*findpeaks*" function in MATLAB. As an option, the minimum interval of the peaks was set to 0.6 s. A cardiac cycle of 0.6 s corresponds to a heart rate of 100 bpm, and the beating cycle is longer than that under the resting state.

From the ECG R-peak and radar-cardio peak, the following two evaluation indices were obtained. The missed radar-cardio peak, which is defined as either a missed or a

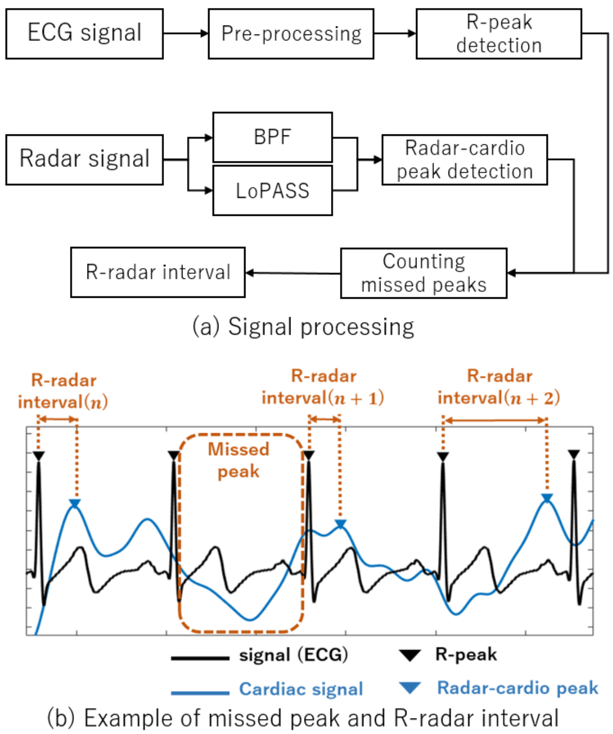

Figure 2. Signal processing procedure and evaluation images: (a) Overview of signal processing (b) Image of missed peaks and R-radar interval segments.

spurious radar-cardio peak relative to the ECG R-peak, was counted and recorded. Missed peaks were excluded from the analysis and adjusted such that the R-peak and radar-cardio peak were in pairs. R-radar interval is defined as the time interval between the ECG R-peak and the radar-cardio peak. From all R-radar intervals, the mean and standard deviation were calculated. Figure 2 (b) depicts a schematic diagram of the calculation of the evaluation index from the signals.

D. Laboratory experiment and clinical application

In this study, we evaluated the best filter for the HRV measurement using controlled data in the laboratory. In addition, we aimed to evaluate the applicability of the HRV filter to radar measurement data of a patient diagnosed with pneumonia. Initially, we evaluated the cardiac signal extraction method using the data measured in the laboratory. First, the 10 healthy students with the following details were considered as subjects— age: 24±5, BMI: 21.3±1.8, six males, and four females. The subjects were restricted to a resting and supine position. Ten minutes of measurement were taken per subject, and a total of 6880 beats were captured. Using the ECG signal as a reference, the number of missed peaks and the R-radar interval were compared to determine the best filter. Second, the best filter was used to implement HRV monitoring for the elderly in a clinical situation. The study was conducted on one patient at the Yokohama Hospital. The patient was 92 years old, a female, and had a fever of 38.7 °C on February 6, 2017, who was subsequently diagnosed with pneumonia. The radar data of five days before and after February 6, 2017 were used. The data were extracted from 5 min of relatively no body movement during the night hours. HRV was estimated from the cardiac signals extracted by the optimal filter. This study was approved by the Ethics Committee of the University of Electro-Communications and Tokyo Metropolitan University.

III. Results

Table 1 presents the results of the number of missed peaks and R-radar intervals of 10 subjects. The LoPASS filter had the lowest missed peaks at 54 and 42 for the I and Q signals, respectively. The mean of the R-radar intervals of 10 subjects was approximately 270–350 ms. This suggested that the radar-cardio peak was present within the R-T interval [19] of the ECG, and it captured the correct peak from a physiological aspect. The LoPASS filter had the smallest SD of 126 ms and 110 ms for I and Q signals, respectively. The results of this study indicated that LoPASS was the most suitable filter for the HRV measurement.

Figure 3 (a) depicts the distribution of the R-radar interval of LoPASS and a BPF of 0.75–5 Hz. The ECG R-peak is located at 0 on the x-axis, and the histogram shows the position of the radar-cardio peaks. According to this picture, the distribution of LoPASS is sharp, and the variation of R-radar interval is small. However, the distribution of BPF is gentle, indicating that the variation of R-radar interval is large owing to the effect of distortion. Here, the distribution is divided into two parts because there are two candidate radar-cardio peaks in one beat, and automatic peak detection cannot distinguish between them. Figure 3 (b) illustrates the detailed waveforms of the cardiac signal extracted using

Table 1. Summarized data of evaluation indicators

	Average [subject=10]					
	I signal			Q signal		
filters	Number of missed peaks	R-radar Interval Mean [ms]	R-radar Interval SD [ms]	Number of missed peaks	R-radar Interval Mean [ms]	R-radar Interval SD [ms]
BPF(0.75-5[Hz])	123	354	218	114	334	190
BPF(0.75-10[Hz])	109	323	197	94	322	178
BPF(0.75-20[Hz])	106	310	193	94	307	172
LoPASS	54	272	126	42	272	110

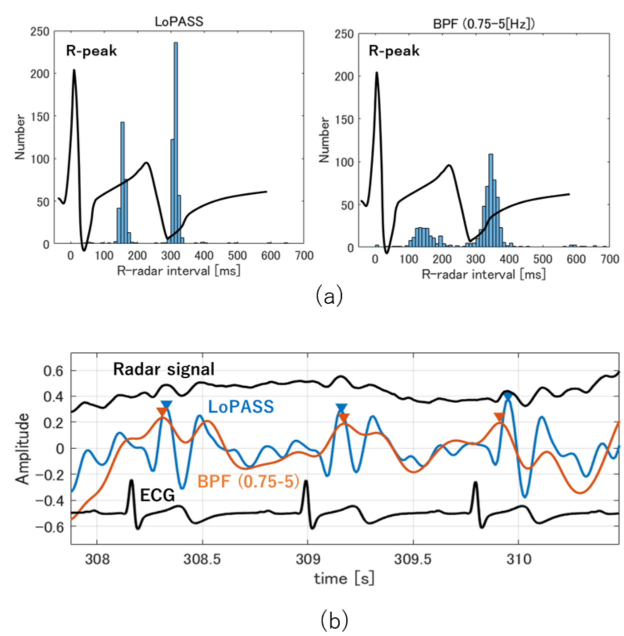

Figure 3. Detailed analysis results of the filter: (a) Distribution of the R-radar interval of LoPASS and BPF (0.75-5 Hz) (b) Waveforms of LoPASS and BPF (0.75-5 Hz)

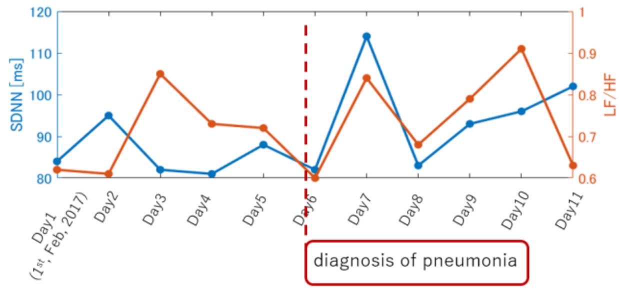

Figure 4. Time series plot of HRV monitoring in the elderly

LoPASS and a BPF of 0.75–5 Hz. This graph shows that the peak of the BPF signal is not synchronized with the radar signal owing to the distortion caused by the filter.

Figure 4 demonstrates the result of monitoring elderly patient by implementing the clinical data using HRV measurement filter. Based on the above evaluation results, LoPASS was introduced as the HRV filter. SDNN and LF/HF were estimated in the time domain and the frequency domain, respectively, where SDNN represents the SD of the peak-to-peak interval, and LF/HF represents the ratio of low frequency (LF) and high frequency (HF) power. These two indexes represent the overall balance between the sympathetic and parasympathetic nervous systems. From Figure 4, we can observe the stagnation of SDNN and the descent of LF/HF a few days before the diagnosis of pneumonia.

IV. Discussion and Conclusion

In this study, we proposed a filter evaluation method based on the R-radar interval to estimate HRV in a monitoring system. The best cardiac signal extraction filter was adopted from the laboratory members' data, and HRV measurement was conducted using clinical data. The evaluation of laboratory data tests indicated that LoPASS was the best extraction method for the HRV measurement, which overcomes the problems of missing the radar-cardio peaks in the radar signal and the distortion of the time domain. In addition, the introduction of an HRV filter using LoPASS facilitated HRV estimation in monitoring elderly people.

There are certain requirements for this system. First, for HRV estimation, it is assumed that there is no body movement, and the signal quality is good. For real-time application, it is necessary to add a technique to distinguish the clean signal and the signal including random movements before applying our system. Second, when the peak detection is automatic, the appropriate peak may not be selected. To address this problem, this study requires a peak estimation algorithm exclusively for cardiac signals.

In conclusion, in this study, we aimed to determine a method to estimate HRV based on non-contact vital sign sensors, which can be applied to elderly patients. The detailed analysis showed that the LoPASS filter exhibited an outstanding effectiveness in achieving the goal.

References

[1] I. J. Brekke, L. H. Puntervoll, P. B. Pedersen, J. Kellett and M. Brabrand, "The Value of Vital Sign Trends in Predicting and Monitoring Clinical Deterioration: A Systematic Review," *PLOS ONE*, vol. 14, no. 1, p. e0210875, 2019.

[2] C. Li, V. M. Lubecke, O. Boric-Lubecke and J. Lin, "A Review on Recent Advances in Doppler Radar Sensors for Noncontact Healthcare Monitoring," *In IEEE Transactions on Microwave Theory and Techniques*, vol. 61, no. 5, pp. 2046-2060, 2013.

[3] T. Matsui et al., "A Pneumonia Screening System Based on Parasympathetic Activity Monitoring in Non-Contact Way Using Compact Radars beneath the Bed Mattress," *The Journal of Infection*, vol. 81, no. 2, pp. e142-e144, 2020.

[4] G. Sun, M. Okada, R. Nakamura, T. Matsuo, T. Kirimoto, Y. Hakozaki and T. Matsui, "Twenty-Four-Hour Continuous and Remote Monitoring of Respiratory Rate Using a Medical Radar System for the Early Detection of Pneumonia in Symptomatic Elderly Bedridden Hospitalized Patients," *Clinical Case Reports*, vol. 7, no. 1, pp. 83-86, 2019.

[5] N. Liu, Z. Lin, J. Cao, Z. Koh, T. Zhang, G. B. Huang, W. Ser and M. E. Ong, "An Intelligent Scoring System and Its Application to Cardiac Arrest Prediction," *In IEEE Transactions on Information Technology in Biomedicine: a Publication of the IEEE Engineering in Medicine and Biology Society*, vol. 16, no. 6, pp. 1324-1331, 2012.

[6] A. Elola, E. Aramendi, E. Rueda, U. Irusta, H. Wang and A. Idris, "Towards the Prediction of Rearrest during Out-of-Hospital Cardiac Arrest," *Entropy*, vol. 22, no. 7, p. 758, Jul. 2020.

[7] F. Khan, J. W. Choi and S. H. Cho, "Vital Sign Monitoring of a Non-Stationary Human through IR-UWB Radar," *4th IEEE International Conference on Network Infrastructure and Digital Content, Beijing, 2014*, 511-514, 2014.

[8] E. Schires, P. Georgiou and T. S. Lande, "Vital Sign Monitoring through the Back Using an UWB Impulse Radar with Body Coupled Antennas," *In IEEE Transactions on Biomedical Circuits and Systems*, vol. 12, no. 2, pp. 292-302, 2018.

[9] B. Lohman, O. Boric-Lubecke, V. M. Lubecke, P. W. Ong and M. M. Sondhi, "A Digital Signal Processor for Doppler Radar Sensing of Vital Signs,", *IEEE Engineering in Medicine and Biology Magazine: the Quarterly Magazine of the Engineering in Medicine and Biology Society*, vol. 21, no. 5, 161-164, 2002.

[10] C. Ye, K. Toyoda and T. Ohtsuki, "Blind Source Separation on Non-Contact Heartbeat Detection by Non-Negative Matrix Factorization Algorithms," *In IEEE Transactions on Bio-Medical Engineering*, vol. 67, no. 2, pp. 482-494, 2020.

[11] C. Chen Ye, K. Toyoda and T. Ohtsuki, "A Stochastic Gradient Approach for Robust Heartbeat Detection with Doppler Radar Using Time-Window-Variation Technique," *In IEEE Transactions on Bio-Medical Engineering*, vol. 66, no. 6, pp. 1730-1741, 2019.

[12] Y. Yao, G. Sun, T. Kirimoto and M. Schiek, "Extracting Cardiac Information from Medical Radar Using Locally Projective Adaptive Signal Separation," *Frontiers in Physiology*, vol. 10, article 568, 2019.

[13] Y. Yao, C. Brüser, U. Pietrzyk, S. Leonhardt, S. van Waasen and M. Schiek, "Model-Based Verification of a Non-Linear Separation Scheme for Ballistocardiography," *In IEEE Journal of Biomedical and Health Informatics*, vol. 18, no. 1, pp. 174-182, 2014.

[14] Changzhi Li and Jenshan Lin, "Random Body Movement Cancellation in Doppler Radar Vital Sign Detection," *In IEEE Transactions on Microwave Theory and Techniques*, vol. 56, no. 12, pp. 3143-3152, 2008.

[15] J. C. Lin, J. Kiernicki, M. Kiernicki and P. B. Wollschlaeger, "Microwave Apexcardiography," *In IEEE Transactions on Microwave Theory and Techniques*, vol. 27, no. 6, pp. 618-620, Jun. 1979.

[16] P. Grassberger, R. Hegger, H. Kantz, and C. Schaffrath, "On noise reduction methods for chaotic data," *Chaos 3*, pp.127–141, 1993.

[17] T. Schreiber, and D. T. Kaplan, "Signal separation by nonlinear projections: the fetal electrocardiogram," *Phys. Rev. E,* vol. 53, issue 5, pp. R4326-R4329, 1996.

[18] J. Pan and W. J. Tompkins, "A Real-Time QRS Detection Algorithm," *In IEEE Transactions on Bio-Medical Engineering*, vol. 32, no. 3, pp. 230-236, 1985.

[19] A. Porta, G. Baselli, F. Lombardi, S. Cerutti, R. Antolini, M. D. Del Greco, F. Ravelli and G. Nollo, "Performance Assessment of Standard Algorithms for Dynamic R-T Interval Measurement: Comparison between R-Tapex and R-T(end) Approach," *Medical and Biological Engineering and Computing*, vol. 36, no. 1, pp. 35-42, 1998.