A comparative study of two methods for sleep respiratory detection

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ABSTRACT

Sleep respiratory signals are among the crucial physiological parameters of the human body, playing a significant role in the diagnosis and treatment of sleep-related disorders such as sleep apnea syndrome. However, current detection methods have certain limitations and are not yet widely applied in practice. This paper selects eight subjects under open indoor conditions to compare the performance of the contact-based piezoelectric method and the non-contact millimeter-wave radar method in sleep respiratory detection across different sleeping postures. The aim is to analyze the differences and characteristics of these methods in clinical applications, providing valuable references for the detection of sleep respiratory signals in clinical practice. Experimental outcomes indicate that the millimeter-wave radar acquisition technique manifests considerable disparities in the intensity of respiratory signals across distinct sleeping orientations, specifically ranking in the order of prone > supine > lateral. This observation underscores the method's heightened responsiveness to alterations in sleeping posture. Notably, when subjects are in the prone position, the peak values of respiratory signals acquired through this technique exhibit a higher degree of consistency. In contrast, the piezoelectric approach yields respiratory signal intensities that remain largely invariant across diverse sleeping postures, thereby affirming its robust stability amidst changes in posture. Additionally, it is noteworthy that the piezoelectric method facilitates the collection of respiratory signals with more stable peak values during both supine and lateral sleeping postures.

Keywords: Sleep Respiratory Detection, Piezoelectric Film Sensor, Millimeter-Wave Radar, Comparative Experiment

1. INTRODUCTION

With the acceleration of modern life, there is an increasing focus on sleep quality, making sleep disorders a growing global issue. According to a study by the World Health Organization, approximately 27% of the global population is affected by sleep problems[1], and this proportion continues to rise.

In the field of sleep medicine, polysomnography[2] (Polysomnography, PSG) is considered the gold standard for evaluating sleep quality. Currently, there are two main methods for sleep respiratory detection: contact-based and non-contact-based methods. Contact-based methods include impedance, respiratory inductance plethysmography, photoplethysmography, and electrocardiogram extraction, which can cause discomfort due to skin contact, restrict body movement, and reduce sleep quality, making them unsuitable for burn patients. Non-contact methods include video detection, piezoelectric detection, and millimeter-wave radar detection. This paper focuses on two non-contact sleep respiratory detection methods: a mattress embedded with a PVDF piezoelectric film sensor and millimeter-wave radar. The mattress embedded with a PVDF piezoelectric film sensor has advantages such as low cost and ease of use in sleep respiratory detection. However, it also has some drawbacks, such as the potential impact of temperature changes on sensor performance and accuracy, and significant interference from body movements during sleep respiratory detection. In 1991, Jansen et al.[3] designed a mattress capable of detecting human motion to extract respiratory signals. Millimeter-wave radar, with its high penetration and precision, can accurately monitor sleep states, making it particularly suitable for long-term and large-scale monitoring needs. However, it also has disadvantages, such as high cost and complex installation and operation. Biological millimeter-wave radar primarily targets the detection of human vital signs[4][5]. In 2015, Dr. Adib et al.[6] published research on using FMCW radar to obtain subjects' respiratory rates.

This paper selects two non-contact sleep respiratory detection methods—one based on a PVDF piezoelectric film sensor and the other on millimeter-wave radar—for a comparative experiment. By comparing the differences and characteristics

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of the respiratory signals collected by the two methods, this study aims to provide effective references for the application of sleep respiratory signal detection.

2. SLEEP RESPIRATORY DETECTION METHOD

2.1 PVDF piezoelectric sensor sleep respiratory detection

Some crystalline materials exhibit piezoelectric effects[7] under external forces, accumulating charges on their surfaces or within, thereby generating voltage. By encapsulating such materials into PVDF piezoelectric film sensors, highly sensitive sensors can detect subtle pressure changes.

Placing the PVDF piezoelectric film sensor between a mattress and the human body, respiratory movements cause slight deformations in the film[8], resulting in changes in electric charge. The mathematical relationship between the output voltage V and the applied force F is expressed as Equation (1) (where d is the piezoelectric constant, and C is the capacitance connected to the piezoelectric element). The small amount of charge output by the piezoelectric sensor under stress is further amplified by auxiliary signal conditioning circuits to capture and convert respiratory signals. Finally, signals are filtered and separated to extract human respiratory signals around 0.2~0.4 Hz. Park et al.[9] placed PVDF piezoelectric film sensors beneath the mattress at the back of subjects to detect respiratory signals.

$$V = \frac{d}{C} \times F \tag{1}$$

2.2 Millimeter wave radar sleep respiratory detection

FMCW radar emits continuous frequency-modulated pulses to measure the distance and velocity of targets[10]. The frequency of the pulse signal linearly increases over time, following a chirp modulation pattern expressed as Equation (2), where f_c is the starting frequency of the pulse signal, T_c is the chirp modulation repetition period, and B is the frequency bandwidth of the modulation.

$$f(t) = f_c + \frac{B}{T_c} t \tag{2}$$

The pulse signal and the target's echo signal are mixed to get the IF signal. Millimeter wave radar measures the distance and speed of the target respectively through range FFT and Doppler frequency shift principle. Breath detection is achieved through the analysis of micro-Doppler effects. The frequency of human respiratory signals ranges from 0.1 to 0.5 Hz, with amplitudes on the body surface varying from 1 to 12 mm.

the relationship between thoracic displacement changes between consecutive pulses and phase variation is expressed by Equation (3), where ΔR represents thoracic displacement during successive pulse period, and λ denotes the wavelength of the pulse signal. By continuously analyzing the phase dynamics of linearly modulated pulses at the target's Range Bin, digital signal processing algorithms can extract respiratory signals from the phase signals[11][12]. In 2020, Emmi Turppa et al.[13] studied the monitoring of vital signs in various sleep scenarios using FMCW radar, validating the practical application of millimeter-wave radar in sleep respiratory detection.

$$\Delta\varphi = \frac{4\pi\Delta R}{\lambda} \tag{3}$$

3. COMPARATIVE EXPERIMENT ON SLEEP RESPIRATORY DETECTION

This study designs signal acquisition experiments for three different sleeping postures. Through comparative analysis of the experimental results, the differences and characteristics of the two detection methods are investigated.

3.1 Experimental preparation

Experimental Subjects: The experiment involved 8 subjects aged between 20 and 31, all in healthy condition without any respiratory or cardiovascular diseases. Basic information, including age, gender, and physical condition, was collected from each subject prior to the experiment.

Measurement Devices: The millimeter-wave radar measurement method utilized the AWR1642BOOST module from Texas Instruments (TI) along with the DCA1000 EVM data capture board. The collected millimeter-wave signals were converted by an ADC and transmitted to a PC for data processing. For the piezoelectric mattress measurement method, a PSP-type flexible piezoelectric film sensor from was used. The signals were filtered and then transmitted to the PC via an RS232 serial port.

Data Collection Procedure: The millimeter-wave radar was positioned 70 cm directly above the subject's chest, while the piezoelectric mattress was placed under the subject's back, ensuring that the piezoelectric film sensor and the millimeter-wave radar were approximately aligned along the same vertical axis, as shown in Figure 1. The subjects were instructed to lie in three positions sequentially: supine, prone, and lateral, with a 1-minute interval between each position. Data from both measurement methods were collected simultaneously and repeated three times. The millimeter-wave radar data were saved as bin files, and the piezoelectric sensor data were saved as csv files.

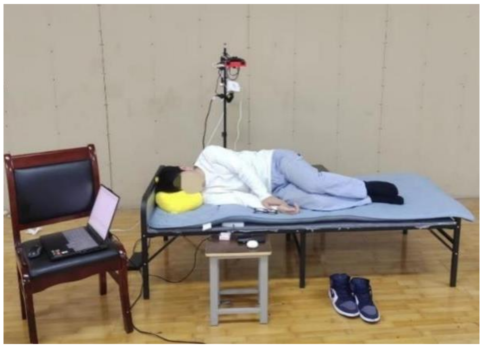

Figure 1. Experimental scene diagram

3.1.1 Supine experiment

Figure 2 illustrates the supine position of the subject lying on the bed with the head aligned flat against the headboard. The millimeter-wave radar and the piezoelectric mattress synchronously sense and capture minute displacements on the thoracic surface caused by respiratory. The millimeter-wave radar collects a total of 1200 frames of data at a sampling rate of 20 Hz. On the host computer, the data undergo preprocessing, MTI (Moving Target Indication), arctangent phase extraction, phase unwrapping, and phase differencing to obtain the phase difference signal. Subsequently, the signal is filtered with a sliding average filter to remove pulse noise and normalized using a 4th-order Butterworth band-pass filter with a cutoff frequency of 0.1 Hz and stop-band cutoff frequency of 0.5 Hz, resulting in the normalized time-domain waveform of the respiratory signal collected by the millimeter-wave radar. The piezoelectric sensor collects a total of 30,000 frames of data at a sampling rate of 500 Hz. The data undergo the same Butterworth band-pass filtering and normalization process to yield the normalized time-domain waveform of the respiratory signal collected by the piezoelectric sensor. As shown in Figure 3, the blue line represents the respiratory signal from the millimeter-wave radar, and the red line represents the respiratory signal from the piezoelectric film sensor.

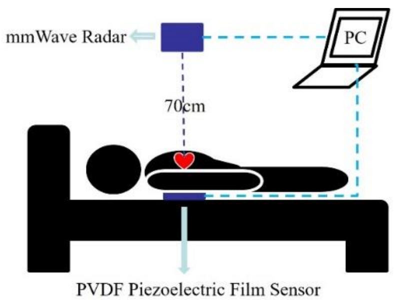

Figure 2. Supine diagram

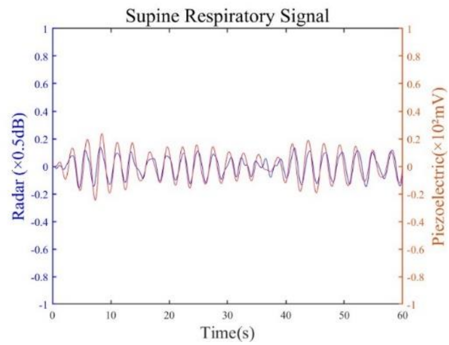

Figure 3. Comparison of supine respiratory signals

The paper separately computes the mean and standard deviation of the respiratory signal peaks within 1-minute interval for both detection datasets, serving as indicators of the average intensity and stability of the respiratory signals. Figure 4 presents the mean and standard deviation of the respiratory signal peaks acquired under the supine sleeping posture. From this, preliminary observations suggest that the ratio of the standard deviation to the mean (Coefficient of Variation, CV) for the piezoelectric method is smaller compared to that of the millimeter-wave radar method.

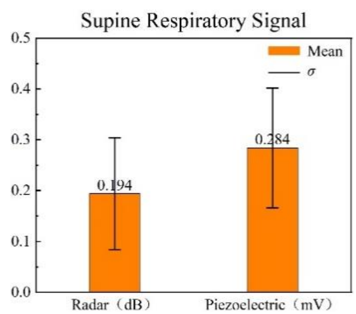

Figure 4. Mean and standard supine respiratory signals

3.1.2 Prone experiment

Similarly to the supine experiment, Figure 5 depicts the mean and standard deviation of the respiratory signal peaks acquired from all subjects in the prone sleeping position. Compared to the aforementioned experiments, it is evident that the peak values of respiratory signals collected via the millimeter-wave radar method are significantly higher in the prone posture than in the supine posture. In contrast, the peak values of respiratory signals obtained using the piezoelectric method do not show any notable differences between the two postures.

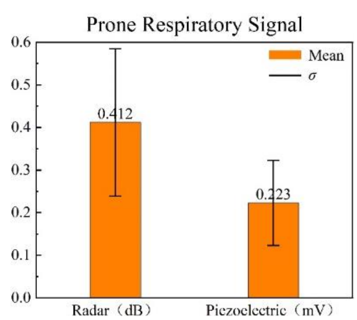

Figure 5. Mean and standard prone respiratory signals

3.1.3 Lateral lying experiment

Similar to the supine experiment, Figure 6 depicts the subject in a lateral sleeping position. It was found that the peak value of the millimeter-wave radar in the lateral sleeping position is significantly lower than in other sleeping positions, whereas the piezoelectric method shows no significant difference.

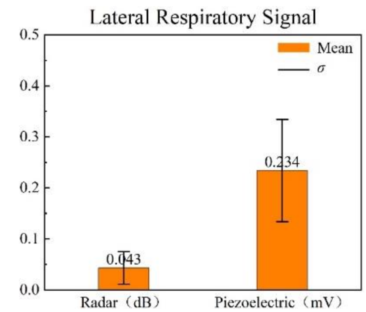

Figure 6. Mean and standard lateral respiratory signals

3.2 Analysis of sleep respiratory detection experiment results

Here are the summaries for the peak respiratory signals in the three sleeping positions (supine, prone, and lateral) presented in Figure 7. The experimental results indicate that the peak respiratory signal collected by the millimeter-wave radar in the lateral lying position is less than 0.02 dB, showing significant attenuation compared to other sleeping positions, ranked from highest to lowest intensity as prone, supine, and lateral. On the other hand, the peak respiratory signal collected by the piezoelectric method ranges between 22 to 28 mV, with no significant changes in respiratory intensity observed during changes in sleeping positions. Additionally, the CV (Coefficient of Variation) for the peak respiratory signal waveforms collected by both sensors was calculated and is shown in Figure 8. The results indicate that the piezoelectric sensor provides more stable respiratory signals in the supine and lateral lying positions compared to the millimeter-wave radar. Conversely, the millimeter-wave radar shows more stable respiratory signals in the prone lying position compared to the piezoelectric sensor.

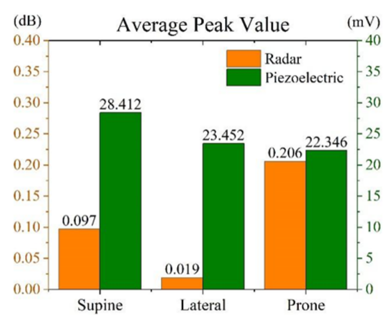

Figure 7. Comparison of respiratory signal means

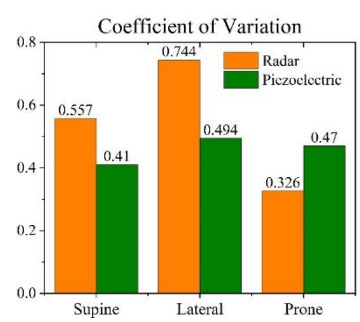

Figure 8. Comparison of coefficient of variation

4. SUMMARY

This paper introduces the principles of two methods for sleep respiratory detection and conducts comparative experiments on respiratory signal detection in three different sleeping postures, involving seven subjects. The experimental results demonstrate that the millimeter-wave radar shows significant variations in respiratory signal intensity across different sleeping positions, with the order of intensity being prone > supine > lateral. In contrast, the piezoelectric mattress method does not exhibit significant differences in respiratory signals across different sleeping positions. Comparing the coefficient of variation (CV) of the respiratory signal peaks across different sleeping postures, the piezoelectric sensor provides more stable respiratory signals in the supine and lateral positions, while the millimeter-wave radar shows more stable signals in the prone position. Based on the experimental design and results, it can be preliminarily concluded that the piezoelectric method is suitable for applications requiring stability, whereas the millimeter-wave radar method is suitable for applications requiring high sensitivity. This work may serve as a reference for clinical applications and research in sleep respiratory detection.

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