

Received November 18, 2021, accepted December 7, 2021, date of publication December 10, 2021, date of current version December 21, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3134280

Remote Measurement of Short-Term Heart Rate With Narrow Beam Millimeter Wave Radar

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This work was supported by the National Natural Science Foundation of China under Grant 61731001.

ABSTRACT Heart rate measurement technology based on Doppler radar can monitor heart rate in real time without direct contact with the skin, which possesses the advantages of convenient operation, comfort and insensitivity to the skin state. However, due to the limitation of radar's performance, heartbeat signals obtained by radar sensor do not have clear peak value like electrocardiograms (ECGs) and pulse waves, which affects its measurement accuracy. Therefore, this paper proposes a non-contact short-term heart rate detection system based on 120 GHz narrow beam frequency-modulated continuous-wave (FMCW) millimeter wave radar. On the basis of improving the signal-to-clutter ratio (SCR) of intermediate frequency (IF) signals with narrow beam, this system applies stochastic resonance algorithm to enhance the amplitude of heartbeat signals submerged in radar system noise, thus enhancing the signal-to-noise ratio (SNR) of heartbeat signals and improving the accuracy of heart rate detection. The short-term heart rate of 10 volunteers is measured at 3 s interval under the condition that the radar sensor was 1 m from the human chest. Experimental results show that compared with the peak count of the reference pulse wave sensor, the results of this system are highly consistent with those of photoplethysmograph (PPG) detection. Finally, those results of heart rate detection are also used to analyze heart rate variability (HRV).

INDEX TERMS Narrow beam millimeter wave radar, short-term heart rate, stochastic resonance, signal enhancement.

I. INTRODUCTION

Short-term heart rate monitoring and analysis play an important role in early warning and treatment of heart disease as well as reducing incidence rate and mortality. At present, electrodes or pulse wave sensors are needed to be stuck on the body surface for heart rate monitoring [1], [2]. This kind of method has been widely recognized in its stability and accuracy of heart rate signal measurement, but it also has some disadvantages, such as body discomfort, not suitable for long-time monitoring, unable to quickly disinfect and so on. Heart rate detection equipment based on Doppler radar, which possesses the advantages of no physical contact and strong penetration, has positive significance in daily health monitoring, medical diagnosis and other fields, and thus has become a research hotspot for new research in recent years [3]–[8]. Using the displacement-phase modulation effect of electromagnetic wave and evaluating heart rate by measuring the phase sequence period of radar IF signal is the

main way of non-contact measurement. For instance, a team composed of Droitcour and others from Stanford University have designed a set of cardiopulmonary monitoring system based on continuous-wave (CW) radar [9]. When the measuring distance is 2 m, the accuracy of heartbeat measurement reaches 80%. They have also analyzed the relationship between absolute displacement and phase changes of chest surface caused by heartbeat. Lawrence Berkeley National Laboratory has developed a FMCW life monitoring radar prototype, the measuring range of which is 0.5–10 m, and the distance resolution of which can reach 0.5 mm [10]. Experiments show this system is more suitable for non-ideal environments such as hospital wards with more clutter and noise interference.

However, owing to the limitation of radar sensors' working characteristics and the very weak amplitude of heartbeat vibration on the chest surface, heartbeat signals are vulnerable to the interference of environmental clutter, radar system noise and respiratory harmonics. The SNR of heartbeat signals obtained by echo phase is low, so it is difficult to accurately detect the peak and valley position

The associate editor coordinating the review of this manuscript and approving it for publication was Cihun-Siyong (Alex) Gong¹.

of heartbeat signals, which are very important for analyzing the irregularity and change of heartbeat by short-time time domain signal. At present, the most commonly used heart rate extraction algorithms in the field of vital signs monitoring radar are fast Fourier transform (FFT) and various nonlinear signal processing methods, and there are few reports on time-domain feature detection method. However, FFT and other algorithms need a long time of heartbeat data to obtain a certain level of data accuracy [11]. Only the average heart rate can be calculated for a period of time, and it cannot realize real-time judgment of abnormal physiological phenomena such as heart rate inequality. As a result, its application value in medicine is limited. Therefore, how to suppress clutter and noise, improve radar phase resolution and enhance heartbeat signal amplitude become the main problems faced by Doppler radar measurement. One possible solution to problems of this kind is to select millimeter wave band which is more sensitive to millimeter mechanical motion as the working frequency of biological radar, and use narrow beam antenna to suppress environment clutter interference and some novel signal processing algorithms have also been introduced to improve the relative amplitude of heartbeat signal and remove clutter interference. For example, Chenwen Liu *et al.* studied the echo pollution caused by multipath effect in radar measurement and presented an effective ghost target removal algorithm [12]. Sasan Bakhtiari *et al.* used 94 GHz radar to measure vital signs and focused the transmitted beam on the target through Gaussian lens. Finally a parameter optimization method based on the nonlinear Levenberg-Marquardt algorithm is used and thus the measurement accuracy is improved [13].

On the basis of what have been analyzed above, this paper studies an short-term heart rate measurement method based on narrow beam millimeter wave radar. We know that the wavelength corresponding to the 120 GHz band is very short, only 2.5 mm. According to the formula of phase and heartbeat vibration displacement, the phase change caused by heartbeat displacement of 0.1-0.5 mm can reach 0.5-2.5 radius, so this wavelength is more sensitive to heartbeat vibration of sub millimeter level. Of course, the antenna in 120 GHz band has small mechanical size and compact structure, which is beneficial to the design of narrow beam lens antenna and the miniaturization of radar. Therefore, we chose 120 GHz radar for short-term heart rate monitoring. Considering that heartbeat signals obtained from the radar sensor are easy to be interfered by respiratory signals and the SNR is low, the envelope method is used to remove respiratory signals and a stochastic resonance algorithm for nonlinear system is proposed to enhance the amplitude of heartbeat signals submerged in radar system noise; then the number of heartbeat signals is detected by peak points searching algorithm to realize the estimation of short-term heart rate.

The rest of this paper is organized as follows. Section II introduces the basic principle and algorithm design of sensor system. Section III describes the parameter setting of the radar. Experimental results are presented and discussed in

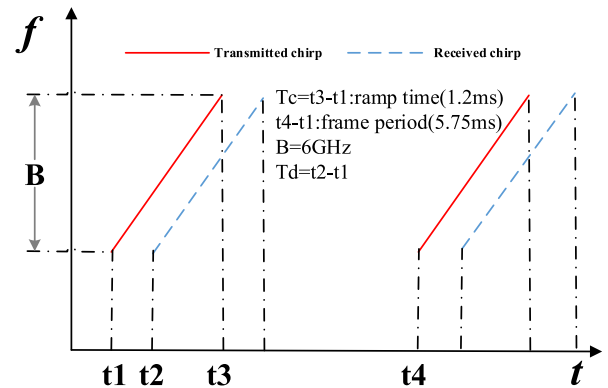


FIGURE 1. Schematic diagram of transmitting and receiving signals.

Section IV and Section V. Finally, Section VI summarizes the results and conclusions of this paper.

II. BASIC PRINCIPLE AND ALGORITHM DESIGN OF SENSOR SYSTEM

A. PRINCIPLE OF FMCW RADAR

There exists direct-current (DC) bias in IF signals due to the high transmission power of CW biological radar. Calibration is required for each use, which makes the operation inconvenient. Therefore, this paper uses FMCW radar to measure short-term heart rate. During the working process of FMCW radar, the FMCW generator at the radio frequency (RF) front-end constantly generates sweep signals whose frequency changes linearly with time, and radiates them out through the transmitting antenna. The radiated electromagnetic waves are blocked by the human body target and then scatter on the skin. Radar's receiving antenna receives the scattering echo of human body in space, which is amplified by low noise amplifier, and then mixed with local oscillator (LO) signal quadrature to output I/Q signals. Then the subsequent signal processing is carried out to extract the breathing and heartbeat information of the human body.

Every FMCW pulse transmitted by radar is a sinusoidal signal whose frequency changes linearly with time. Such a signal is called chirp signal in this paper, whose sweep bandwidth is denoted as B and sweep duration is denoted as T_c . The receiving signal at the output port of the receiving antenna is amplified by a low noise amplifier, and then mixed with the transmitting signal to generate the IF signal. Relevant information of human target can be obtained by analyzing the IF signal. As shown in Figure 1, time delay of the transmitting signal leads to the instantaneous frequency difference between transmitted and received signals. By analyzing the frequency of IF signals, we can get the human target's distance information [14].

The radar's transmitting signal can be expressed as:

$$S_t = A_t * \cos(2\pi f_{\min} t + \pi \frac{B}{T_c} t^2 + \phi(t)) \quad (1)$$

where A_t is the power strength of the transmitting signal, f_{\min} is the sweep's initial frequency, $\phi(t)$ is the phase noise of the

transmitter, T_c is the duration of chirp signal, and B/T_c is the sweep slope of the transmitting signal.

For a single point target, when thermal noise and other RF defects are ignored, the transmitting signal will be reflected when it encounters the scattering point. As the echo signal is received by the receiving antenna, it is the delay form of the FMCW signal transmitted in formula (2):

$$S_r(t) = A_r \cos(2\pi f_{\min}(t - t_d) + \pi \frac{B}{T_c}(t - t_d)^2 + \phi(t - t_d)) \quad (2)$$

Suppose that there is an ideal point target directly in front of the radar beam, and the distance is R_0 . The object has a tiny displacement $d(t)$ with time at this position. Represent the weak vibration changing with time with $R(t) = R_0 + d(t)$, and then the signal delay can be expressed as:

$$t_d = \frac{2(R_0 + d(t))}{c} \quad (3)$$

where c is light speed. The quadrature mixing of reflected signals and local oscillator of the radar is realized through I/Q dual channel, and then IF signals are obtained through a low-pass filter. Ignoring items with smaller values in the formula, the radar IF signal can be expressed as:

$$S_{IF} \approx kA_r A_r \cos(2\pi \frac{2BR_0}{cT_c}t + \frac{4\pi(R_0 + d(t))}{\lambda} + \Delta\phi(t)) + n(t) \quad (4)$$

where $n(t)$ stands for the noise.

It can be seen that the IF signal's phase is proportional to the small change of chest wall displacement. As long as the chirp signal is transmitted continuously for many times, the weak vibration on the body surface can be sampled. Therefore, weak vibrations at the target location, or micro chest vibrations caused by respiration and heartbeat, can be known by demodulating phase changes at the target position. However, for FMCW radar implemented by phase locked loop (PLL) or direct digital synthesis (DDS), the performance of its VCO (voltage controlled oscillator) is not ideal. And in the process of realizing linear frequency sweep, the phase noise $\phi(t)$ of the transmitter changes with time, which directly leads to the residual phase noise $\Delta\phi(t) = \phi(t) - \phi(t - t_d)$ of the IF signal obtained by mixing the received signal with LO changes randomly with time in a certain range. Therefore, after extracting the phase of radar IF signal in sequence, it is easy to find tiny random noise in the phase sequence.

B. STOCHASTIC RESONANCE ALGORITHM

From what have been analyzed above, we can know that phase sequences obtained from biological radar IF signals are mainly composed of respiratory signal, heartbeat signal and radar system noise, and heartbeat signal is approximate periodic signal. Therefore, we use stochastic resonance algorithm to enhance heartbeat signals and thus realize the measurement of short-term heart rate. The stochastic

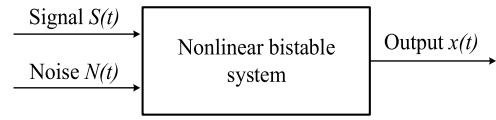


FIGURE 2. The block diagram of stochastic resonance system.

resonance detection method based on nonlinear theory is to transform part of noise energy into periodic signal energy output, improve SNR and realize weak periodic signal detection under certain conditions by using the positive synergy of noise in nonlinear system [15]–[17]. The block diagram of stochastic resonance system is shown in Figure 2. By inputting signal $S(t)$ and noise $N(t)$ into nonlinear system, solving differential equation and outputting $x(t)$, target signals with enhanced amplitude can be obtained [18].

The nonlinear bistable model adopted in this paper is the classical nonlinear dynamic model: Langevin equation (LE) and the bistable system can be described by the following LE equation:

$$\frac{dx}{dt} = -\frac{dV(x)}{dx} + S(t) + N(t) \quad (5)$$

where $x(t)$ is system output function, $S(t)$ is weak periodic signal input into the system, $N(t)$ represents noise whose intensity is D , while $V(x)$ is nonlinear bistable potential function, whose mathematical expression is:

$$V(x) = -\frac{1}{2}ax^2 + \frac{1}{4}bx^4 \quad (6)$$

where a, b are bistable system parameters.

The potential function substituted, the LE equation of the bistable system affected by white noise $N(t)$ and external periodic driving force $A \sin \omega_0 t$ can also be written as:

$$\frac{dx}{dt} = ax - bx^3 + A \sin \omega_0 t + N(t) \quad (7)$$

The bistable system possesses two potential wells and one potential barrier, whose height is $\Delta U = a^2/4b$. In the absence of external signal and noise, threshold of maintaining bistability is $A_c = \sqrt[3]{4a^3/27b}$.

Stochastic resonance can be generated by the bistable system when input signals meet certain requirements. According to Kramers' escape rate theory, input signal frequency f should be less than transition rate R_k of Brownian particles between two potential wells in the system, as shown in the following formula:

$$R_k = \frac{a}{\sqrt{2\pi}} \exp\left(-\frac{\Delta U}{D}\right) \quad (8)$$

At this time, when amplitude of input signal $A_0 > A_c$, system output changes periodically between the two potential wells, but noise is also very easy to act on the output, leading to over resonance. When $A_0 \ll A_c$, energy of the signal itself is too weak, and system output cannot cross the barrier, resulting in under resonance phenomenon. Therefore, only when $A_0 < A_c$ and the amplitude is similar can the input signal, noise and bistable system match and produce

stochastic resonance [19]. In engineering, its expression is: the SNR of the system output reaches the peak value, which greatly enhances the effective components of the signal, thus improving the detection ability of extracting periodic signal from strong noise, especially weak signal.

III. EQUIPMENT AND PARAMETER SETTING

To achieve accurate measurement of short-term heart rate, a set of non-contact vital signs monitoring system based on FMCW radar in the 120 GHz band is built in this section, which is based on the principle of FMCW radar and the practical application requirements of human vital signs monitoring. The sensor system's front end adopts the SiRad Easy[®] Evaluation Kit by Silicon Radar GmbH Germany [20], whose transmitting antenna power is -3 dBm, and maximum frequency sweep range is 119 GHz-126 GHz [21]. In addition, we choose SiRad Easy[®] Evaluation Kit, which adopt a PLL structure when transmitting FMCW pulses. The circuit structure realizes the high linearity frequency sweep of the radar through the automatic control principle, ensuring high spectral purity and low harmonic power. Measurement results show that the phase noise of the transmitted signal spectrum can be as low as -80 dBc/Hz.

A. SETTING FMCW SWEEP BANDWIDTH AND FRAME PERIOD

According to radar's range resolution formula $R_{res} = c/2B$, the wider the radar's bandwidth is, the higher the range resolution is. However, since the linearity of radar's voltage controlled oscillator (VCO) is poor below 119.5 GHz and above 125.5 GHz, in this paper the sweep range is set at 119.5-125.5 GHz. At this time, the range resolution is 2.5 cm. Ability to distinguish different regions near the human chest and stronger sensitivity to body shaking across distance units make this system more conducive to the effective extraction of heart rate. For FMCW radar, each chirp can be regarded as a sampling of the micro vibration on the chest surface. According to Nyquist sampling theorem, chirp repetition rate should be higher than twice the maximum heart rate in order to keep complete heart rate information. Medical statistics show that a normal person's heart rate is generally lower than 3 Hz. Therefore, we set the radar's chirp repetition period to 5.75 ms, which can be converted into 174 Hz. This frequency is much higher than that of heart rate, and thus can meet the requirements.

B. NARROW BEAM LENS ANTENNA

In order to improve the SCR of the effective scattering points in the heart and weaken other clutter interference in the space, this paper explores to install a low sidelobe and small volume antenna lens at the front end of the radar transceiver antenna, which uses ellipsoid made of polytetrafluoroethylene to refract electromagnetic wave so that its 3 dB beam width can be narrowed. The 3 dB beam width after adding lens antenna is about $\pm 2.5^\circ$, while the main lobe gain is 28.7 dB. Greatly concentrated in the direction of the main beam, the energy

TABLE 1. The details of 10 volunteers.

ID	Gender	Age	Height(cm)	Weight(Kg)	Health Condition
1	M	22	178	65.2	Good
2	M	22	170	72.0	Good
3	M	23	170	65.0	Good
4	M	26	174	75.0	Good
5	M	30	175	69.0	Good
6	M	25	177	64.0	Good
7	M	28	172	74.0	Good
8	F	32	158	50.0	Good
9	M	29	173	67.0	Good
10	F	25	156	46.0	Good

forms a very narrow beam in space. At the same time, all scattering points in the region are located in the same distance unit. Thus scattering points in other areas of human body and background environment in space can be filtered by this device. Furthermore, the low side lobe lens antenna can also weaken the side lobe radiation energy in other directions, avoiding the influence of side lobe on target detection.

IV. RESULTS AND ANALYSIS

A. MEASUREMENT EXPERIMENT

This experiment aims to explore the feasibility and accuracy of non-contact short-term heart rate measurement using millimeter wave radar. Therefore, we recruited 10 volunteers, who are 22-32 years old, 156-178 cm tall, weighed 46-74 kg and without no obvious physical and psychological diseases, as subjects to verify the performance of the device. The details of 10 volunteers are shown in Table 1.

Before the experiment, all subjects fully understood the working principle of monitoring vital signs with biological radar and radar performance, and signed the informed consent form. Then the following experimental steps were carried out.

- 1) The volunteers sit at a distance of 1 m in front of the radar, keep calm and breathe normally. And the radar's main beam direction is vertically aligned with the heart through laser calibration. Meanwhile, connect the cardiovascular monitor and photoelectric pulse wave sensor according to the specification. Figure 3 shows the schematic diagram of the experiment.
- 2) Turn on the cardiovascular monitor 3 minutes in advance until the display screen can show the heart rate in real time. Then the biological radar is powered on, and the AD acquisition card collects and exports the radar IF data and photoelectric pulse wave sensor data in real time. The monitoring experiment lasts 100 s and every volunteer experiences the process of data collection repeatedly for 2 times.
- 3) Aim the biological radar's main beams at the volunteer's back and make the volunteer keep stationary. Then collect IF signals for 2 times so as to study the noise characteristics of the biological radar system.



FIGURE 3. The picture of the measurement experiment.

- 4) Save the collected radar IF signals and pulse wave signals respectively for subsequent processing.

B. SIGNAL PROCESSING

After radar IF signals and pulse wave signals are collected, corresponding signal processing and short-term heart rate extraction should be carried out to evaluate the accuracy of heart rate measurement. In order to calculate the short-term heart rate based on biological radar signals, it is necessary to process the radar IF signals corresponding to the subjects and thus get the waveform of the heartbeat signal. The specific steps are as follows:

- 1) Perform fast Fourier transform (FFT) on the IF signal corresponding to each chirp, extract the real part and imaginary part of FFT corresponding to the frequency of spectrum peak point, and calculate the phase by means of inverse trigonometric function $\arctan(I/R)$ to obtain the phase sequence waveform varying with time.

- 2) Adjust the phase caused when the chest displacement is greater than $\lambda_{\max}/4$ [14]. Figure 4(a) shows the time-varying phase sequence after jump compensation, from which it can be seen that the phase sequence is a composite signal composed of heartbeat signal, respiratory signal and radar system noise, the respiratory signal is much stronger than the heartbeat signal. According to Figure 4(b), the radar system noise amplitude is slightly less than the heartbeat signal amplitude. Because the minimum amplitude of heartbeat is about 0.1mm, the corresponding phase change is less than $\pi/6$, and the amplitude of noise is in the same order of magnitude.

In order to eliminate respiratory signals' influence on heart rate measurement, we use envelope mid-line method to remove them. As the normal breathing cycle is about 4 times of the heartbeat cycle, the displacement of the body surface caused by breathing is more than 5 times of the heart rate. Therefore, as long as we select the average respiratory cycle as the fitting step length when extracting the envelope, the envelope step length is about 4 times of the heartbeat cycle. As a result, the envelope of the heartbeat signal will not be extracted, and the midlines of the upper and lower envelope will only change with the respiratory signal. When taking the upper and lower envelopes of the raw phase sequence,

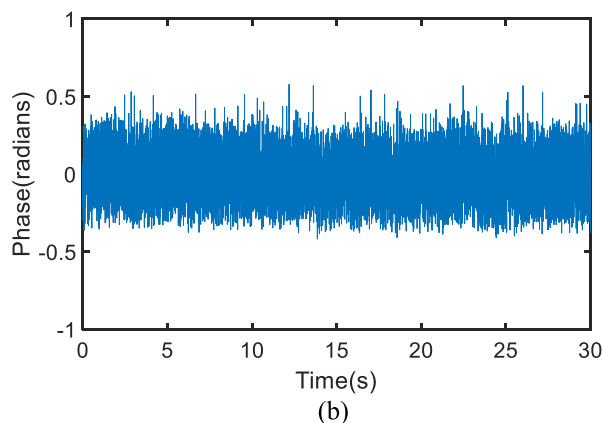
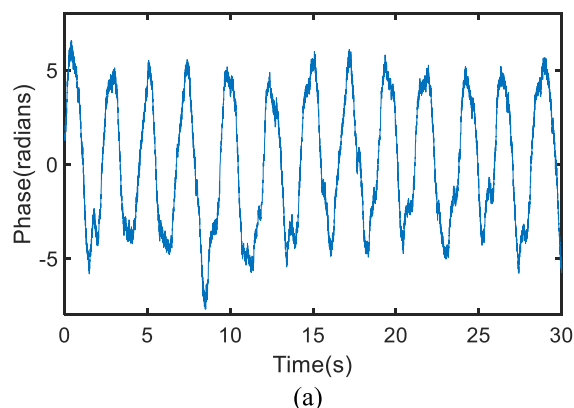


FIGURE 4. (a) The phase sequence measurement results obtained when the radar beam is aimed at the heart and (b) the phase sequence measurement results obtained when the radar beam is aimed at the person's back.

we use the envelope function of MATLAB. According to the characteristics of human respiratory cycle, selecting an appropriate envelope step (about 5.75s) can make the upper and lower envelope follow the trend of respiratory signal, thus removing the fundamental wave and suppressing harmonics of respiratory signal. That is, we first take the middle line of the upper and lower envelope of the raw phase data sequence in Figure 4(a), the step size of envelope extraction is set to 100 points, then subtract the envelope's center line from the original phase data and finally obtain the phase sequence mainly composed of heartbeat signals and radar system noises, whose waveform is shown in the following Figure 5. FFT is performed on the data in Figure 5 for spectrum analysis, as shown in Figure 6. We can see that after removing the respiratory signal by envelope method, the amplitude of fundamental wave, harmonics of respiratory signal in heartbeat signal has been significantly reduced.

It can be found that the heartbeat signal is submerged in the radar system noise. Therefore, we try to take phases sequences, in which fundamental waves of respiratory signals are removed, as input signals of the nonlinear stochastic resonance system, and optimize the structure parameters a and b by genetic algorithm to obtain the heartbeat signal with enhanced amplitude. Here, we initialize the optimization

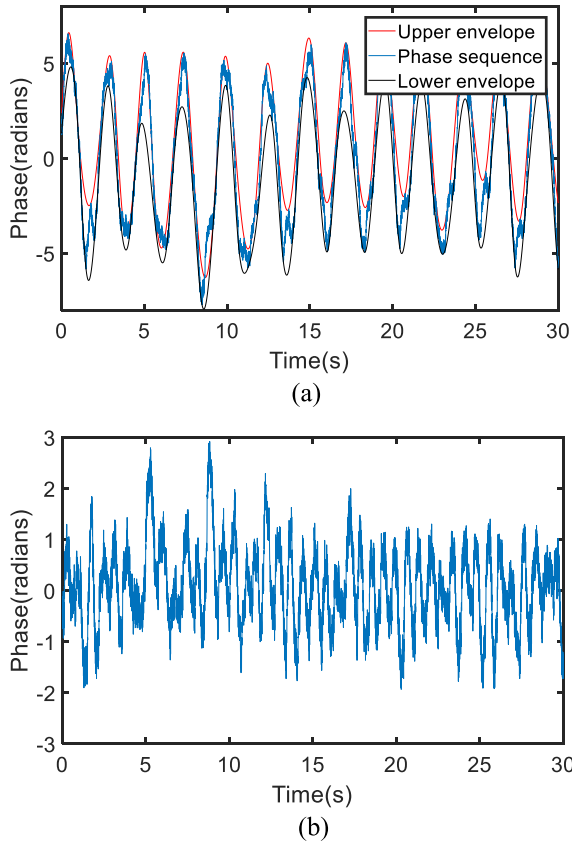


FIGURE 5. (a) Eliminate respiratory signals by envelope method and (b) phase sequence after removing respiratory signals.

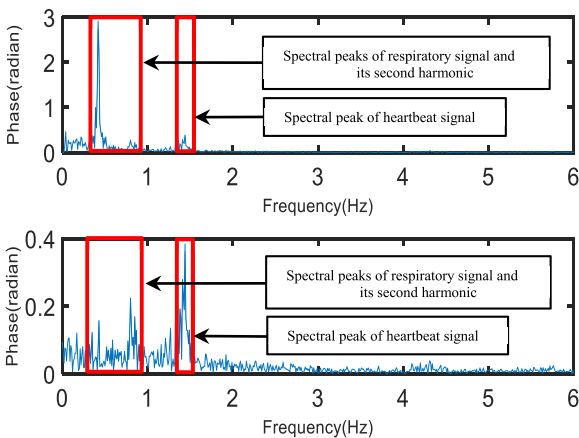


FIGURE 6. The FFT plot of raw phase sequence (upper) and FFT of phase sequence after envelope method (lower).

range of a and b respectively as $[-100\ 200]$ and $[-100\ 39000]$, set the fitness function of genetic algorithm as the SNR of heartbeat signals, and enhance the characteristics of heartbeat signals by adjusting the structural parameters a and b . Then we solve the Langevin differential equation and thus acquire the time domain diagram of stochastic resonance system output based on genetic algorithm [22], as shown in Figure 7.

By comparing Figure 5(b) and Figure 7, it can be seen that after the system parameters a and b are optimized

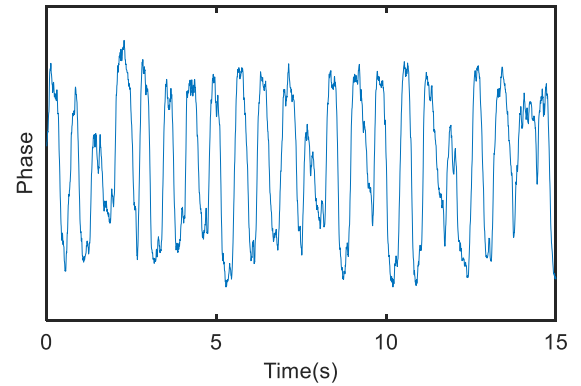


FIGURE 7. Heartbeat signal after noise reduction by stochastic resonance algorithm.

by genetic algorithm, the time-domain characteristics of heartbeat signals in phase sequence are more obvious, and the SNR is improved. In order to quantitatively evaluate the effect of stochastic resonance algorithm on heartbeat signal enhancement and denoising, FFT is conducted on the signals in Figure 5(b) and Figure 7 respectively to obtain their spectrum and normalize them. Since the heart rate of person without disability must be lower than 5 Hz, we regard all the parts above 5 Hz in the normalized spectrum as noise, and calculate the arithmetic sum of squares respectively as the total relative noise energy P_b and P_a . Finally, it is calculated that $P_a/P_b=15\%$. It can be seen that the relative noise energy of heartbeat signal is reduced by 85% through stochastic resonance algorithm. However, for the low-frequency noise contained in the heartbeat signal, stochastic resonance algorithm cannot effectively remove it.

From the time-domain waveform, it can be found there still exists burr on the heartbeat signal waveform, and the period and amplitude are not stable, so it belongs to non-stationary signal. Therefore, we use the Gaussian smoothing filter [23] to smooth them and then find the peak on the curve to determine the short-term heart rate. The smoothed heartbeat signal is shown in Figure 8. Compared with the pulse waves collected in the same period, their cycles have high consistency. The processing flow chart of the radar IF signal is shown in Figure 9.

C. STATISTICS OF SHORT-TERM HEART RATE MEASUREMENT RESULTS

The short-term heartbeat signal of 3 s, were taken as a calculation unit. Figure 10 shows the short-term heart rate test results of a volunteer. Compared with the results of PPG signal peak detection, The absolute value and change trend of heart rate in the two groups were basically the same, except for individual heart rate values. It can be seen that the heart rate measurement results obtained by the above algorithm can better reflect the change of heart rate with time. Ten volunteers' heart rate test results were statistically analyzed. We use Pearson correlation coefficient to evaluate the effectiveness of heart rate measurement results measured

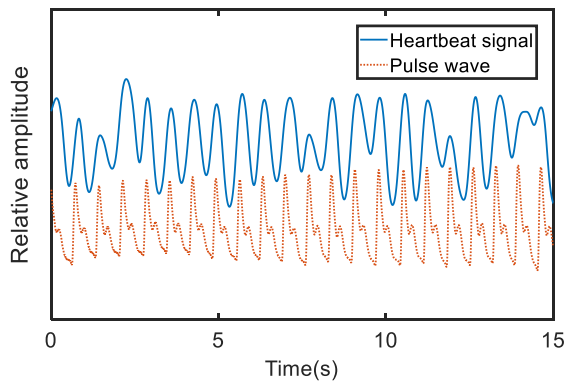


FIGURE 8. Comparison diagram of smooth filtered heartbeat signal and pulse wave signal.

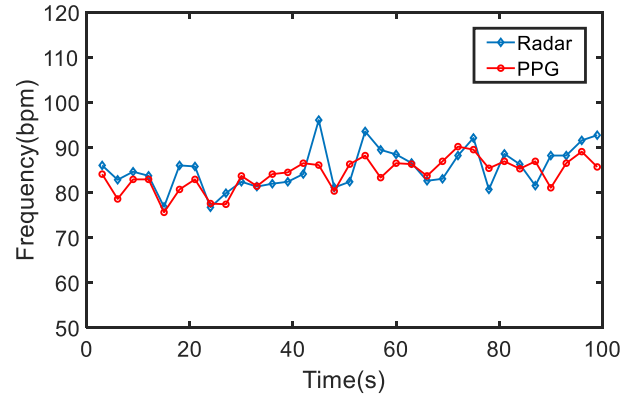


FIGURE 10. Heart rate estimation using 3s heartbeat signal.

expression of short-term heart rate as follows.

$$Accuracy_rate = \frac{HR_{ref} - |HR_{radar} - HR_{ref}|}{HR_{ref}} \times 100(\%) \quad (10)$$

where HR_{ref} is the heart rate obtained from the number of peaks in the pulse wave, and HR_{radar} is the heart rate obtained from the phase data through stochastic resonance algorithm by using radar sensor. The average accuracy of all those heart rate values in Figure 10 can reach 96.56%, from which it can be seen that the short-term heart rate extraction algorithm in this paper is effective. See Table 2 for the average accuracy of 10 groups of measurement results.

As we all know, a person without disability’s heart rate is not absolutely regular. The autonomic activity of sinoatrial node is regulated by sympathetic nerve and vagus nerve [24], and its changes are related to nerve center pressure reflex and respiratory activity. This mechanism leads to the normal heart stroke interval changing with time in a certain range. For patients with arrhythmia, continuous heart rate recording can be used to evaluate the risk of arrhythmia, and HRV refers to the change of heart rate cycle difference. Research on HRV is of great significance for early diagnosis, monitoring and prognosis evaluation of cardiovascular disease. HRV analysis is a signal analysis process to obtain the information of autonomic nervous system, cardiovascular system and so on through the transformation processing of small fluctuations of heart rate. HRV analysis heart rate methods are often divided into three categories: time domain analysis, frequency domain analysis and nonlinear analysis [25], in which the time domain analysis theory is mature and the significance of each index is clear and thus is widely used in clinical medical experiments. Time domain analysis is a kind of statistical method which calculates the change of heart rate through statistical discrete trend analysis. Since we can’t accurately measure the time of each heartbeat cycle, we use the average heart rate of 3s to evaluate HRV. Here, we define two time-domain parameters to characterize HRV.

1) Standard deviation of normal to normal intervals (SDNN): Evaluate the overall change of HRV to reflect the average variability of heart rate in ms [26]. The larger the

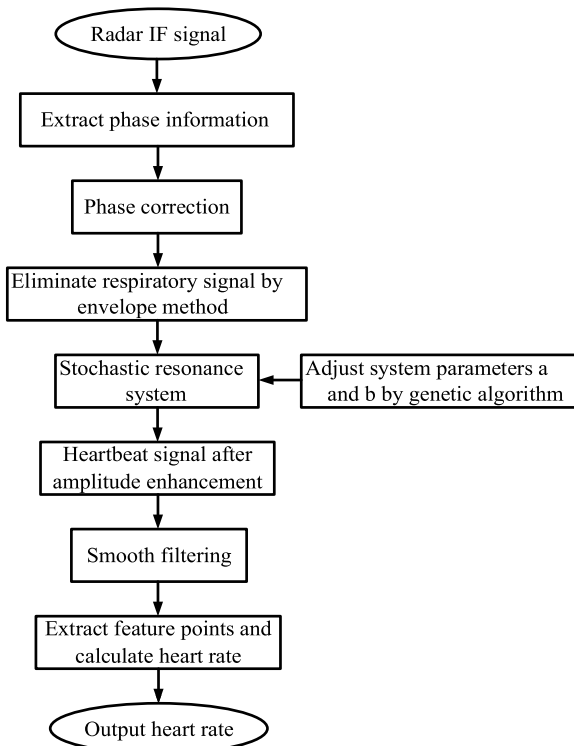


FIGURE 9. Digital signal processing method for short-term heart rate measurement.

by radar and PPG. The Pearson correlation coefficient can be expressed as R_{icc} :

$$R_{icc} = \frac{N \sum x_i y_i - \sum x_i \sum y_i}{\sqrt{N \sum x_i^2 - (\sum x_i)^2} \sqrt{N \sum y_i^2 - (\sum y_i)^2}} \quad (9)$$

Compared with the PPG test results, the R_{icc} of them was 0.7364, 0.6779, 0.7496, 0.6614, 0.7795, 0.8199, 0.7589, 0.8454, 0.8445 and 0.7410 respectively. The statistical results show that there is a significant correlation between them. At the same time, in order to evaluate the accuracy of 3-second heart rate results, we define the accuracy calculation

TABLE 2. The R_{icc} , ACC., AVG., SDNN, and pNN50 parameters of 10 tests.

Subject	R_{icc}	ACC.(%)	AVG.(ms)		SDNN(ms)		pNN50	
			Radar	PPG	Radar	PPG	Radar	PPG
1	0.7364	97.13	708.1	709.4	39.2	39.3	0.2581	0.0645
2	0.6779	96.11	687.2	692.4	41.6	42.0	0.3871	0.1935
3	0.7496	95.62	755.8	760.9	55.9	56.6	0.4196	0.1613
4	0.6614	96.56	704.9	714.0	38.1	39.1	0.2903	0.1613
5	0.7795	97.11	778.8	783.1	48.4	48.5	0.2581	0.0323
6	0.8199	97.54	844.8	849.3	47.1	47.3	0.4516	0.3226
7	0.7589	95.72	768.8	788.8	58.7	62.8	0.3545	0.0645
8	0.8454	96.90	738.1	734.6	55.6	55.7	0.4194	0.2584
9	0.8445	96.27	823.2	828.4	63.6	64.3	0.3548	0.0968
10	0.7410	96.83	727.9	734.1	46.7	47.4	0.2258	0.3230
Paired t -test	—	—	0.8072		0.8414		0.0006	

Avg., mean value of heartbeat intervals; ACC., average accuracy rate of heart rate.

TABLE 3. Comparison of the heart rate measurement results with different radar types and methods.

Ref.	Radar type and operating frequency	Estimation time(s)	Algorithm	HR(%)	Published year
[14]	FMCW radar 77 GHz	12.8	FFT	80	2019
[27]	CW radar 2.45 GHz	5	Reassigned Joint Time-Frequency Transform	95	2011
[28]	SFCW radar 3.3 GHz	18	State space method	94.3	2015
[29]	FMCW radar 120 GHz	3	CEEMDAN and Fast-ICA	97	2021
[30]	Harmonic Radar 12 and 24 GHz	40	FFT	95.68	2014
This work	FMCW radar 120 GHz	3	Stochastic resonance algorithm	95.62	

HR(%), accuracy rate of heart rate.

value, the higher the degree of variation. If the difference between the average adjacent heartbeat cycles of 3 seconds is recorded as $\Delta t = t(n) - t(n-1)$, the expression of SDNN is:

$$SDNN = \sqrt{\frac{1}{N-1} \sum_{n=2}^N (\Delta t(n) - \bar{\Delta t})^2} \quad (11)$$

where $\bar{\Delta t}$ is the average heartbeat cycle.

2) Percentage of interval difference between adjacent heartbeat cycles which are ≥ 50 ms (pNN50): it represents the sudden change of heartbeat interval and reflects the activity of vagus nerve.

The short-term heart rate characteristics within 100 s are counted, and the heart rate parameters of all subjects are shown in Table 2, from which it can be seen that the results obtained by radar measurement method are very close to those measured by PPG, and the paired t -test results show that there is no statistical difference for SDNN. The relative error of SDNN is less than 6.53%. However, for the parameter pNN50, the two statistical results are quite different. The reason is that after the respiratory signal is

removed by envelope method, there will still exist clutter and respiratory harmonics with small amplitude in the remaining phase sequence, resulting in poor stability of heartbeat signal after stochastic resonance algorithm and greater difference between adjacent heartbeat signal cycles, which leads to a deviation of some heart rate values from their correct values.

To a certain extent, SDNN obtained by this method can accurately reflect HRV. Previous studies have shown that SDNN and other indicators show good stability in the analyses of short-term HRV, which is independent of the analysis time. Of course, pNN50 parameters still can not achieve a high accuracy as PPG at present. Short-term HRV analysis can reflect the dynamic changes of the autonomic nervous system. Compared with ECG and PPG analyses, it can reflect the stress response of the autonomic nervous system more quickly and sensitively.

We compared the heart rate measurement results of the radar system with other similar work, as shown in Table 3. As can be seen from the table, the method we used has achieved satisfactory performance. Compared with [14],

millimeter wave radar is used in both works, but our heart rate estimation time is only 1/4 of that in [14], and the accuracy is higher than that in [14]. [27] and [28] adopts low-frequency microwave radar, and the measurement accuracy has basically reached the same level as our work, but the heart rate estimation time is still longer than ours. Their radar sensors are much larger than ours. We have combined CEEMDAN (complete ensemble empirical mode decomposition with adaptive noise) and Fast-ICA (fast independent component analysis) algorithm to estimate the 3-second short-term heart rate in [29], its accuracy is higher than that of stochastic resonance algorithm. The disadvantages of this method are also obvious. Due to the endpoint effect of CEEMDAN algorithm, its measurement time can not be too short. In this regard, stochastic resonance algorithm has advantages. In reference [30], harmonic radar is used to measure heart rate, and the probability of error within ± 2 bpm is higher than our work. However, it takes 40 s to evaluate heart rate every time. Moreover, they did not do a detailed HRV analysis. In fact, since the proportion of clutter and noise in heartbeat signals measured by radar is relatively high, there are relatively few references using biological radar for HRV estimation at present.

V. DISCUSSION

As an important means of non-contact detection of human physiological parameters, biological radar measurement method uses Doppler radar to collect chest vibrations outside the human heart, analyzes changes of IF signals' phase information through signal processing algorithm, extracts heartbeat signals, and detects and estimates the corresponding parameters. In this paper, a short millimeter wave biological radar with a wavelength of 2.5 mm is used, which is more sensitive to the sub millimeter mechanical vibration of the heartbeat. Besides using envelope method to remove respiratory signal, nonlinear stochastic resonance algorithm is also used to suppress radar system noise and enhance heartbeat signal. Although the research on non-contact heart rate and heart rate variability measurement based on camera image photoplethysmograph (iPPG) technology has achieved good results [31], the measurement method based on narrow beam millimeter wave radar adopted in this paper has the advantages of convenient use, simple operation and no calibration, which is more conducive to the application and promotion of non-contact measurement methods.

Of course, there still exist some shortcomings in this paper. For one thing, only a small number of subjects-ten volunteers received measurements. For another, all those subjects were aged between 22 and 32 without any cardiovascular disease. Therefore, under pathological conditions such as arrhythmia, the effectiveness of the radar equipment and algorithm needs to be further verified. In addition, although the HRV estimation of 3-second short-term heart rate is realized in this paper, it is still faced with great technical difficulties to calculate the HRV of medically defined single cycle heartbeat signal.

VI. CONCLUSION

A short-term heart rate measurement method based on millimeter wave radar is presented in this paper. Two characteristics of narrow beam lens antennas' reflected wave are utilized by this method: one is its high SCR, the other is that its IF signal phase is mainly affected by radar system noise. Then, on this basis, the stochastic resonance algorithm is used to improve the SNR of heartbeat signal and enhance the relative amplitude of heartbeat signal, thus realizing the measurement of heart rate in 3 s. Human body experimental results show that the sensor can accurately measure heart rate, has high consistency with the reference results measured by pulse wave sensor. However, in terms of heart rate variability analysis, some parameters obtained by the system still can not achieve the same accuracy as PPG method. Therefore, the extraction algorithm of short-term heart rate still needs to be continuously improved to suppress wrong heart rate values. In the environment that is not suitable for ECG and PPG measurement, the measurement method based on millimeter wave radar technology can provide a new idea for the measurement and analysis of short-term heart rate. For non-professional vital signs monitoring and recording, this measurement system has a good practical prospect in terms of comfort.

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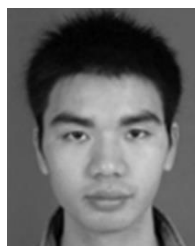
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