

# Noncontact Monitoring of Infant Apnea for Hypoxia Prevention Using a K-band Biomedical Radar

Li Wen<sup>#</sup>, Shuqin Dong<sup>#</sup>, Yi Wang<sup>\$\*^{\wedge}</sup>, Changzhan Gu<sup>#1</sup>, Zheng Tang<sup>\$\*^{\wedge}</sup>, Zhiwei Liu<sup>\$\*^{\wedge}</sup>, Junfa Mao<sup>#</sup>

<sup>#</sup>State Key Laboratory of Radio Frequency Heterogeneous Integration, and MoE Key Lab of Artificial Intelligence, Shanghai Jiao Tong University, Shanghai, China

<sup>\$</sup>Department of Neonatology, International Peace Maternity and Child Health Hospital, Shanghai Jiao Tong University School of Medicine, China

<sup>\*</sup>Shanghai Key Laboratory of Embryo Original Disease, China

<sup>^</sup>Shanghai Municipal Key Clinical Specialty, China

<sup>1</sup>changzhan@sjtu.edu.cn

**Abstract**—Every year many newborns will have apnea which easily leads to a lower level of oxygen saturation i.e. hypoxia. Traditional methods for apnea monitoring usually involve skin contact, so they might cause discomfort or even skin damage to the infants. In this paper, a noncontact infant cardiopulmonary monitoring technique aiming at prompt apnea detection is proposed based on a K-band continuous-wave biomedical radar sensor system, which is custom designed to be DC-coupled with an adaptive digital tuning function. Since the chest motions of infants can be detected by radar in a noncontact way, the respiratory movements can then be demodulated for apnea monitoring. Clinical trials have been carried out and the results show that both precise respiratory movements and apneas with different duration can be well monitored. It suggests the possibility for the proposed technique to be employed inside and outside the clinic.

**Keywords**—biomedical radar, millimeter wave, infant apnea.

## I. INTRODUCTION

Every year hundreds of thousands of preterm infants are born worldwide, and more than half of them have apnea, which may lead to a lower level of oxygen saturation (SpO<sub>2</sub>) i.e. hypoxia, coming with a reduction in heart rate (HR) [1]. Long-term adverse effects such as retinopathy and neurodevelopmental disorders might happen if infants with recurrent prolonged apnea were not noticed promptly.

Electrocardiograph (ECG), impedance pneumography (IP), and photoplethysmography (PPG/pleth) are universally used for clinical infant cardiopulmonary monitoring, providing information about HR, respiratory rate (RR), and SpO<sub>2</sub> respectively. However, the occurrence of hypoxia is usually noticed when the decrease of SpO<sub>2</sub> is alerted by the monitor. It reveals that there is still a lack of apnea monitoring techniques for early hypoxia prevention in the clinic. Besides, all the traditional sensors involve skin contact, which might cause discomfort or even skin damage to the infants.

Therefore, methods to achieve noncontact monitoring of infant apnea are increasingly attracting attention. One of the common methods is based on vision, using depth cameras [2] or infrared cameras [3]-[4] to extract high-precision chest and abdomen displacements of infants. Nevertheless, the vision-based method faces the problems of a large amount of data processing and high power consumption. Laser [5], as another

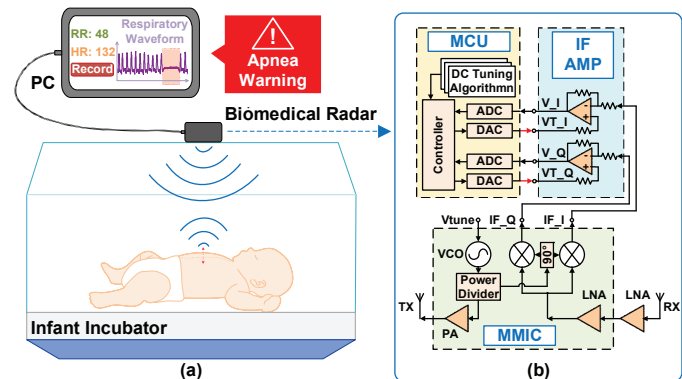


Fig. 1. Overall solution: (a) the schematic diagram of the proposed radar-based noncontact infant respiration monitoring technique; (b) the block diagram of the custom-designed biomedical radar sensor system.

existing noncontact apnea monitoring method to extract the infant's abdomen motions, is flawed, for long exposure to laser causes damage to the infant's skin.

In this paper, a noncontact infant cardiopulmonary monitoring technique aiming at prompt apnea detection is proposed, which is based on a compact K-band continuous-wave (CW) biomedical radar sensor system. Compared with the existing methods, millimeter wave has advantages in terms of its noncontact detection, insensitivity to light, high precision, high penetrability, low power consumption, and little harm to infants. The proposed radar-based technique can accurately extract not only the information of infant respiratory and heartbeat (HB) signals but also the occurrence of apnea, laying a good foundation for early hypoxia prevention, which is a novel work as the previous related studies focus more on the short-time eupnea monitoring.

## II. THEORY AND SYSTEM DESIGN

The schematic diagram of the proposed radar-based noncontact infant respiration monitoring technique in this paper is shown in Fig. 1 (a). In common, preterm infants and newborns with a weight of fewer than 1.5 kilograms live in the infant incubators during the observation period, as they are prone to hypoxia for their immature respiratory systems.

Therefore, the custom-designed *K*-band biomedical radar system is placed at the top of the infant incubator which is about 0.6 meters right above the infants in the supine position. The radar sensor system continuously transmits millimeter waves that propagate through the incubator toward the chest and abdomen regions of infants and then are backscattered to the radar. Meanwhile, the cardiopulmonary activities of the infant such as respiration and heartbeat modulate the millimeter waves in the phase. After receiving the backscattered modulated millimeter waves, the radar system downconverts and adaptively amplifies them for applicable baseband outputs that can be transferred to computing devices. Then the real-time radar output waveforms as well as the RR and HR information can be displayed on the computer terminal, from which the occurrence of apnea can be detected.

The proposed *K*-band biomedical radar sensor system is a DC-coupled CW interferometric radar transceiver, which is sensitive to measure accurate relative displacements of low frequency, such as respiration and heartbeat. Fig. 1 (b) shows the block diagram of the radar system, which is mainly divided into two parts: the radio frequency (RF) circuit and the baseband circuit. The RF circuit includes the custom designed antennas, a low noise amplifier (LNA), and a millimeter wave integrated circuit (MMIC) of 24 GHz silicon germanium process, while the baseband circuit consists of an intermediate frequency (IF) amplifier circuit and a micro control unit (MCU). Due to the direct conversion architecture, the output signals contain DC offsets that may saturate the amplifiers. Thus, a DC tuning algorithm is written in the MCU to adaptively adjust the offsets to make full use of the dynamic range of the amplifiers. The continuous adjustment process is carried out in real time and can cope with sudden changes. Besides, the Digital-to-Analogue Conversions (DAC) within the MCU enable the direct serial transmission between the radar system and other computing devices, making the system portable and friendly to set up in practice.

Since the phases of the radar output signals contain information about the cardiopulmonary activities of the infant, an accurate phase demodulation is of great importance during signal processing. However, when the phase change caused by the detected displacements exceeds a wavelength of the millimeter wave transmitted by the radar system, the signals demodulated using the traditional demodulation algorithms may face the problem of phase discontinuity. Therefore, the modified differential and cross multiply (MDACM) algorithm [6] is used in case in this paper for linear demodulation, and the desired relative displacements can be derived as

$$X[n] = \frac{\lambda}{4\pi} \sum_{k=2}^n I[k-1]Q[k] - I[k]Q[k-1], \quad (1)$$

where  $\lambda$  is the wavelength, while  $I[n]$  and  $Q[n]$  are the digital orthographic radar outputs whose amplitudes and DC offsets have already been calibrated. The MDACM algorithm achieves higher linearity and robustness by avoiding the arctangent transformation and the square calculation of data.

Generally, the demodulated displacement is a combination of respiration and heartbeat signals. In a common state, the RR

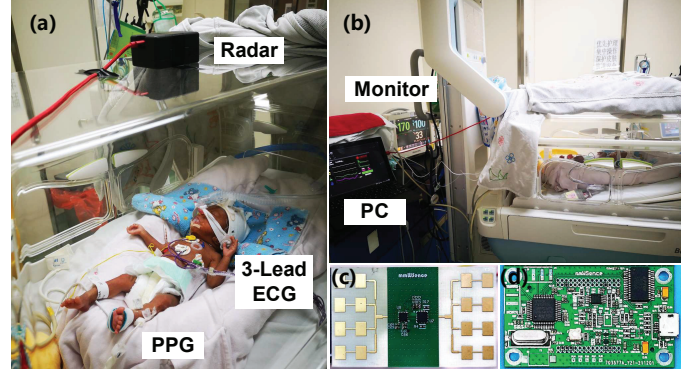


Fig. 2. The experimental setup in the clinical environment: (a) the radar system is set up at the top of the infant incubator, with electrodes and a PPG sensor attached to the infant's body and foot respectively; (b) the display and transmission of the collected data; (c) the RF PCB; (d) the baseband PCB.

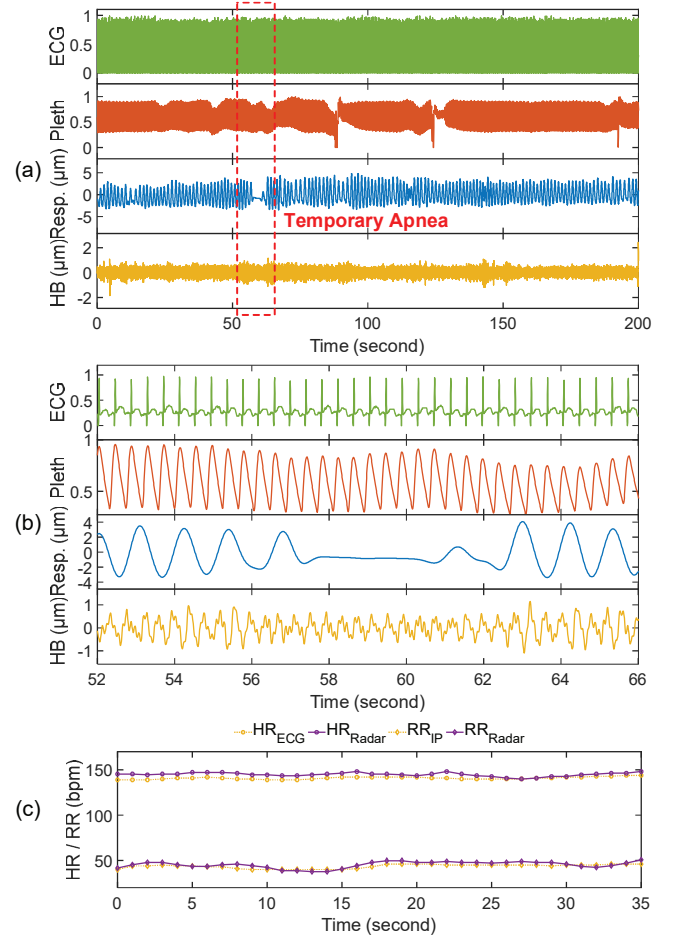


Fig. 3. The monitoring results of an infant with normal cardiopulmonary activities: (a) signal waveforms detected by multiple sensors; (b) the enlarged temporary apnea interval; (c) the comparison of HR and RR obtained from the proposed radar-based technique and traditional methods.

of an infant is usually within the range of 0.5 to 1.5 Hz, while the HR is usually greater than 1.7 Hz. When the apneic events happen, there is only heartbeat information contained in the relative displacement. Therefore, the respiratory and heartbeat signals can be separated by filters or other algorithms, and the

corresponding RR and HR can be obtained through the fast Fourier transform (FFT).

### III. EXPERIMENT AND RESULTS

The experiments were carried out in the Neonatal Intensive Care Unit with permission. Infants weighting less than 1.5 kilograms were subjects recruited for this paper. The setup is shown in Fig. 2 (a) and (b), where the proposed radar system was installed at the top of the incubator and the infant body was within the radar detection range. Meanwhile, electrodes were attached to the infant's skin to obtain ECG and IP signals, and a sensor was attached to the foot for pleth signal. The radar system was connected to the personal computer (PC) using a USB cable for data display and storage, while data from other sensors were shown on the monitor. All the sensors worked at the same time, and data was synchronized by timestamps. Fig. 2 (c) and (d) show the RF and baseband printed circuit board (PCB) of the radar system respectively. The two PCBs have the same size and can be connected with pin headers. The entire radar system is packaged in a custom-designed case for easy installation and transportation.

Fig. 3 shows the monitoring results of an infant with normal cardiopulmonary activities, where she was in a eupnea state but has a short apnea period of 3 seconds. It is noted that temporary apnea without a drop in SpO2 and HR is a normal phenomenon for newborns. Fig. 3 (a) shows the comparison of the 200-second waveforms obtained by multiple sensors, comprised of ECG signal, PPG signal, respiratory and heartbeat signals processed from radar data. The short apneic event is not captured by traditional sensors, but can still be detected by radar, which is more obviously shown in Fig. 3 (b). The respiratory signal is a smooth periodic waveform with a low frequency, whose amplitude changes with time and falls to zero during the apneic event. On the other hand, the heartbeat signal is relatively high-frequency with detailed information. Fig. 3 (c) displays 35-second RR and HR results calculated from the separated respiratory and heartbeat signals, both of which are close to the reference values with mean errors below 5 bpm. These results prove that the proposed technique is able to accurately reconstruct the micrometer-level respiration and heartbeat signals of infants.

Fig. 4 shows the monitoring results of an infant who has serious apneas that cause hypoxia. Fig. 4 (a) demonstrates the occurrence of an apnea: the infant was in the eupnea state at the beginning, then she stopped breathing for about 3 minutes where there were occasional weak breaths and a drop of HR and SpO2, and finally she breathed as normal, increasing the HR and SpO2. Fig. 4 (b) is a short period during the apneic event as marked in Fig. 4 (a) with a dotted box, where the displacement contains only the heartbeat signal, having a great consistency with the reference signals. Whereas, Fig. 4 (c) enlarges a eupnea period that is also marked, and it shows a combination of respiration and heartbeat in the displacement. It is also seen that high accuracy can be achieved by the proposed technique. Besides, the occurrence of apnea can be detected much earlier than the moment when SpO2 begins to decrease, making the early warning of hypoxia possible.

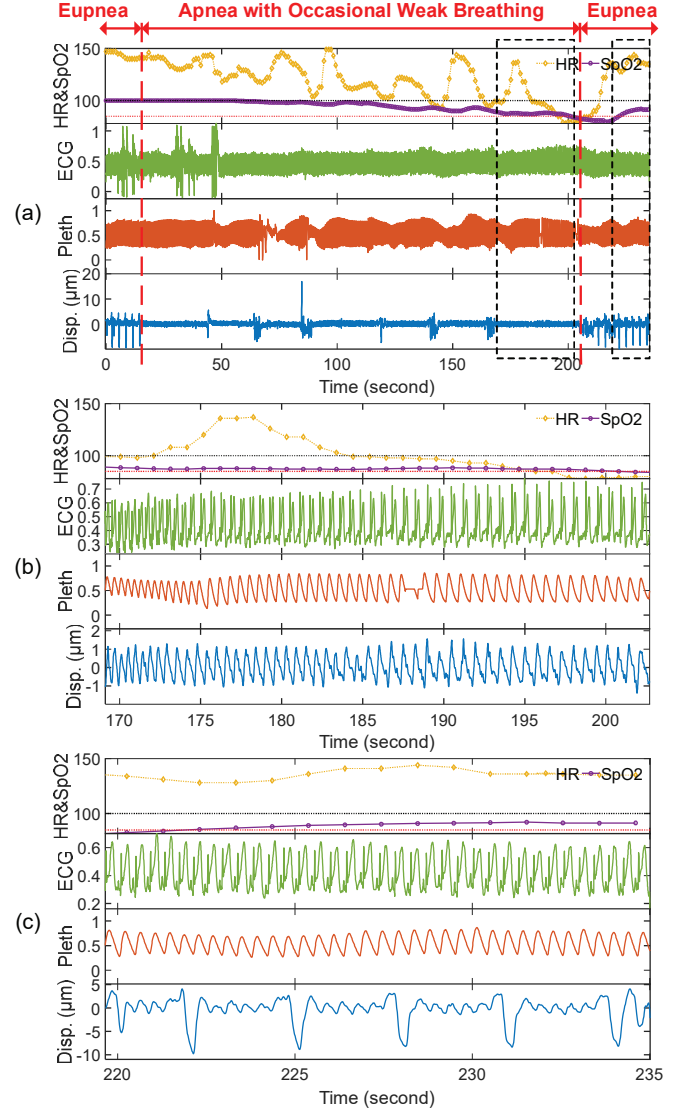


Fig. 4. The monitoring results of an infant with apnea: (a) signal waveforms detected by multiple sensors; (b) the enlarged prolonged apnea period; (c) the enlarged eupnea period.

### IV. CONCLUSION

A noncontact technique based on a K-band biomedical radar is proposed for infant cardiopulmonary monitoring, which includes information about respiration, heartbeat, and the occurrence of apnea. Clinical experiments and results reveal the accuracy of the proposed technique and its feasibility for hypoxia prevention.

### ACKNOWLEDGMENT

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