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Verification of a Non-Contact Vital Sign Monitoring System Using an Infant Simulator

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Abstract—**In this paper, experimental result using a 5.8 GHz Doppler radar to monitor the variations of vital signs of an infant simulator under different medical conditions is presented. The infant simulator can mimic cardiovascular derangements seen in critically ill infants. The result demonstrates the system is capable of tracking a majority of the changes in heart rate and respiratory rate. Analysis suggests possible techniques for further improvement, such as direct coupling circuit, carrier frequency tuning and spectral analysis.**

Keywords—**Cardiovascular, Doppler radar, heart rate, infant simulator, respiratory rate.**

I. Introduction

DOPPLER radar systems have been used for non-contact detection of vital signs and various test results have been reported [1]-[4]. One of the potential health applications that may result in a significant impact in reducing mortality is monitoring sleeping infants to reduce Sudden Infant Death Syndrome (SIDS) [1]. However, in the published literature to date there has been a lack of experimental data to verify the effectiveness of using such a system to detect apnea or lack of respiratory effect which leads to SIDS. While an adult test subject can be instructed to hold their breadth, an infant cannot.

In this paper, a high fidelity human infant simulator (METI) [2] developed for training medical professionals to experience realistic clinical conditions is used to verify the performance of a non-contact vital sign radar sensor. The vital signs of the infant simulator can be varied by computer control to produce various changes in the heart rate and respiratory rate which mimic pathologic conditions. During the experiment, the infant simulator was programmed to behave in a baseline state and several abnormal states including bradypnea, tachypnea, bradycardia, etc. The heart rate, respiratory rate and associated tidal volume were changed from the baseline state in a systematic manner. The Doppler radar sensor used in the experiment has an output power of below 2 dBm and a detection range of around 1 m, while the required output power of a UWB heart rate sensor was 10.92 dBm with a limited detection range of 15 cm [3]. Therefore, the developed Doppler radar can be a better candidate for monitoring babies' health conditions. The accuracy of using the non-contact radar sensor to track the changes in vital signs in normal and abnormal situations was analyzed.

The experimental results show that the radar system can

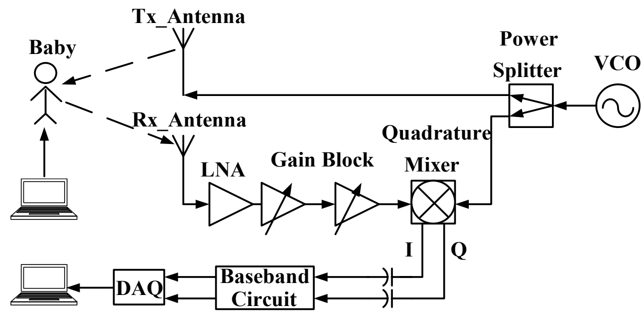


Fig. 1 Block diagram of 5.8G Doppler radar system

detect normal vital sign signals accurately and track the change in vital signs during abnormal conditions. However, when vital signs become weak and with a lot of background noise caused by walking and talking of people nearby, it will be hard for the radar sensor to detect the relatively weak vital sign signals from high level background noise, unless smaller carrier wavelength is used to improve the sensitivity. Other errors caused by the electronic circuits and signal processing can be eliminated or, at least reduced through the modification of circuits and further spectral analysis.

II. System

A. Doppler radar system

The block diagram of the radar system is depicted in Fig. 1. The phase of the reflected wave is modulated by the chest wall movement of the target, and is demodulated into quadrature baseband signals. The baseband signal, either I or Q channel, can be expressed as:

$$\begin{aligned} B(t) &= \cos[\frac{4\pi}{\lambda} \bullet x(t) + \Delta\phi(t)] \\ &= \cos[\frac{4\pi}{\lambda} \bullet [m_h \sin(2\pi f_h t) + m_r \sin(2\pi f_r t)] + \Delta\phi(t)] \end{aligned} \tag{1}$$

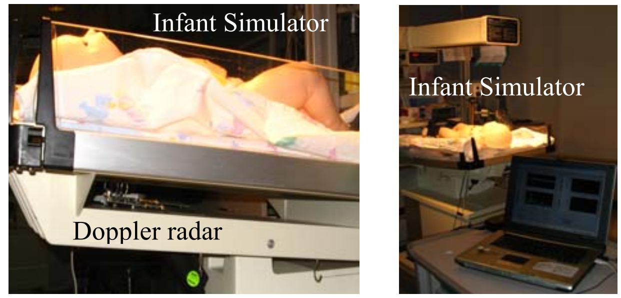
where λ is the carrier wavelength, $x(t)$ is the infant's chest wall displacement due to the respiration and heartbeat, m_r and f_r are the amplitude and frequency of respiration, m_h and f_h are those of heartbeat, $\Delta\Phi(t)$ is the total residual phase that can be eliminated through complex demodulation [4]. It should also be noted that there are two AC coupling capacitances between the mixer and baseband circuit to block the DC components.

B. *Infant simulator*

The infant simulator manufactured by METI provides an appropriate representation of a three- to six-month old infant. The system uses two umbilicals for control. One is fluidic/pneumatic umbilical, the other is electrical umbilical. These two umbilicals are attached to the Power/Communications Unit (PCU) interface panel to generate the automatic and realistic physiological response of an infant whose vital signs are controlled by software. The specific software is installed on a Macintosh workstation.

III. EXPERIMENT

The experiment was carried out in the Neonatal Intensive Care Unit (NICU) at Shands Hospital at the University of Florida. Fig. 2 shows the setup of the experiment. The radar system was placed underneath the crib where x-rays can be taken through a non-metal structure. The radio wave can also penetrate through and reach the infant simulator. The



(a) (b)

Fig. 2. Experimental set up. (a) close shot (b) distant shot

baseband signal from radar sensor was fed to the laptop through a DAQ and a Labview program was designed to perform real time monitoring and signal processing. The experiment was conducted through 18 continuous events. In each event, the respiratory rate (RR), heart rate (HR), and tidal volume (TV) were controlled and changed by the software. Typical clinical ill syndromes such as tachypnea

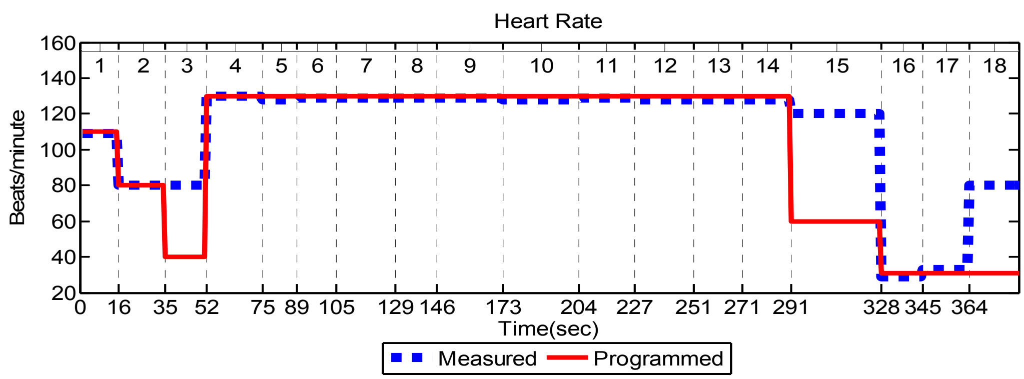


Fig. 3. Measured heart rate vs. programmed heart rate.

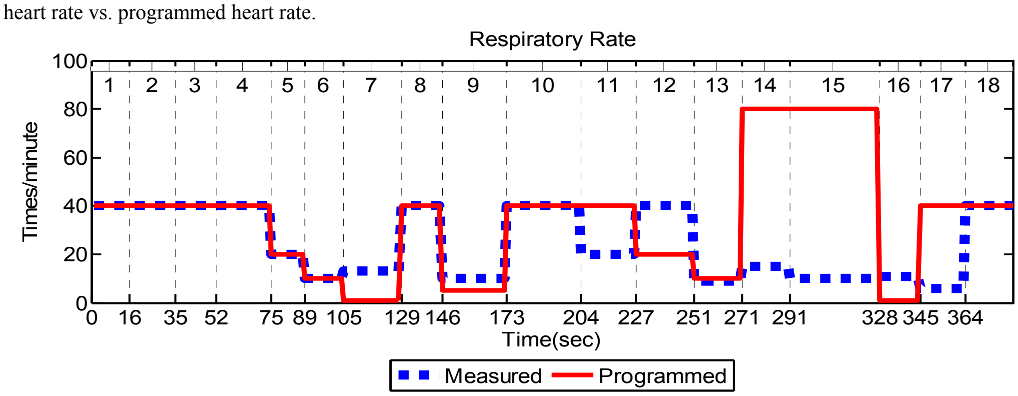


Fig. 4. Measured respiratory rate vs. programmed respiratory rate.

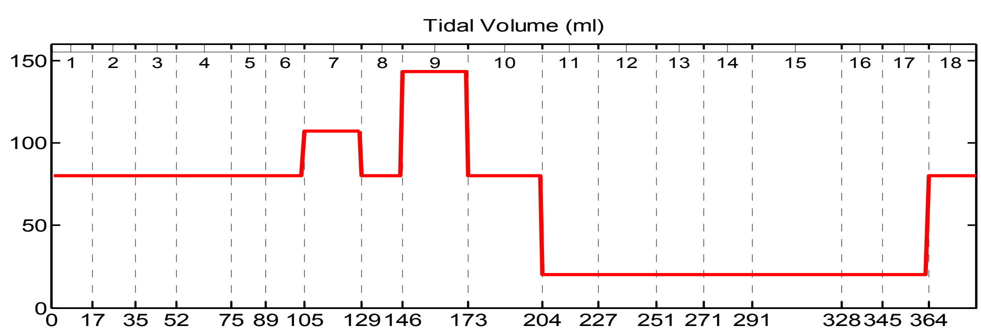


Fig. 5. Programmed Tidal Volume of each event.

(Event 14 and 15) and bradypnea (Event 7 and 9) and other special cases were simulated. Fig. 3 and Fig. 4 show the measurement results of heart rate and respiratory rate of all events respectively, both with the programmed values plotted for comparison. Fig. 5 is the programmed respiratory tidal volume of each event. Bigger TV indicates larger amplitude of respiration. When TV drops to 20 ml, the breathing becomes very weak.

The experimental results proved that the radar sensor can achieve accurate detection results when the infant simulator was in a baseline or normal physiologic state. Although the results have some deviation to the programmed values when detecting the infant under abnormal conditions, they can reflect the change of vital signs under abnormal conditions and provide approximate data that are useful for initial diagnose of specific syndromes. Analyses of the typical cases are presented as follows.

A. Baseline State

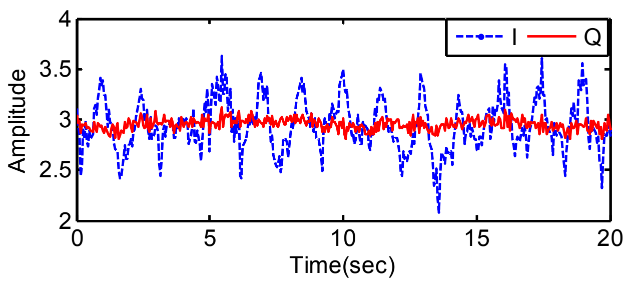


Fig. 6. Measured time-domain baseband signal with programmed RR=40, HR=130.

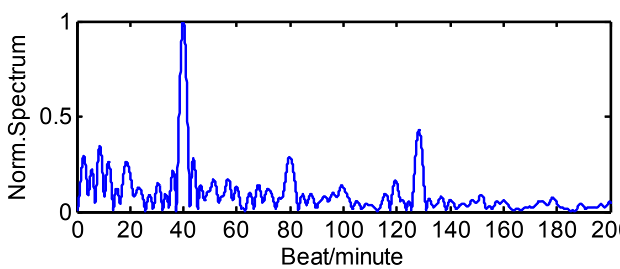


Fig. 7. Normalized measured baseband spectrum with programmed RR=40, HR=130.

At the beginning, the infant simulator was programmed to have normal vital signs. Since the average HR and RR of a normal newborn infant are 130 and 40, these two values were chosen as the baseline state in the program. Fig. 6 and Fig. 7 show the time-domain and normalized spectrum of measured baseband signal under this situation. It can be seen from Fig. 7 that there are two strong frequency components located at 40 and 130 respectively. Normally, the heart rate is always faster than respiratory rate, and the amplitude of respiration activity is larger than that of heart beat. Therefore, the strongest frequency component located at 40 was determined to be the respiratory rate and the second strongest peak at 130 represents the heart rate.

B. Bradypnea

In Event 7 and Event 9, the infant simulator was programmed to have a very low respiratory rate of RR=1 (0.017Hz) and RR=5 (0.04Hz) respectively. Because of the DC blocking capacitor used in the system, the frequency components near DC are attenuated and cannot be accurately detected from the spectrum. That is the reason why the system can only achieve accurate results of relatively high rate vital signs and will lose the low rate information near DC. This problem can potentially be solved by introducing a direct coupling in the circuit without a capacitor so that DC and low frequency components can pass through and be detected.

C. Faint Breathing

It can be seen from the measurement results that starting from Event 11, the accuracy was degraded, especially for the respiratory rate. This is attributed to the large decrease of tidal volume that makes the respiration amplitude drop significantly such that the weak respiratory signal was overwhelmed by the background noise.

In this situation, higher carrier frequency should be used to increase the detection sensitivity. For the 5.8 GHz radar system, the carrier wavelength is approximately 5.2 cm, the phase modulation index $4\pi/\lambda$ in (1) is too small to have an evident effect. If the frequency is increased by 10 times, the wavelength will be comparable to the small chest wall movement when the respiration is weak. Thus, the accuracy should be improved by using higher carrier frequencies.

D. Heart Rate Equals to the Harmonic of the Respiratory Rate

In Event 3, both RR and HR were set at 40. Due to the nonlinear phase modulation effect and the harmonics of movement itself, there exists the 2^{nd} harmonic of RR=40, which is 80. If judging by common sense that heart rate is always higher than respiratory rate, the 2^{nd} harmonic of respiratory rate would be considered as the heart rate mistakenly.

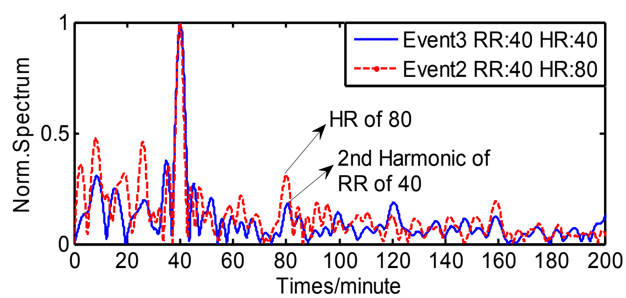


Fig. 8. The comparison of normalized spectrums of measured baseband signal of Event 2 and Event 3

However, looking further into the spectrums of Event 3: RR=40, HR=40 and Event 2: RR=40, HR=80, the subtle difference between these two cases can be found. Fig. 8 shows the comparison of the measured spectrums of Event 2 and Event 3. It is easy to notice the difference at the location of 80: the amplitude of the 2^{nd} harmonic of RR=40 is lower than the amplitude of HR=80 that really exists in Event 2. Therefore, two approaches can be adopted to avoid this kind of problem. The first method is to use lower carrier frequency so that the nonlinear phase modulation effect is reduced, which results in a baseband signal spectrum containing only f_h and f_r without harmonics that could cause confusion. The second approach is to set a detection threshold. If the amplitude of a frequency component is lower than the threshold, it will be determined as harmonic. If it is above the threshold, it can be regarded as useful signal.

E. Tachypnea and Bradycardia

Based on vital sign reference charts [5], the normal RR for a newborn infant is 30-50 and the normal HR is 100-170. Occasionally, the RR of an infant will go faster than the upper limit of 50 with its HR dropping below 100 at the same time. In this situation, the infant would be diagnosed to have both tachypnea and bradycardia. This special case was simulated in Event 15, where HR=60 and RR=80. Because the respiratory TV is weak, the respiration component may become comparable to the heartbeat in spectrum. In this situation, it is easy to mistakenly judge that RR=60, and HR=80, which is just the opposite result of the actual case. Fortunately, using absolute spectrum can potentially solve this problem to identify the vital signs correctly.

The abovementioned detection method is using the frequency difference between respiration and heartbeat to distinguish these two vital signs. However, the difference of strengths of vital sign signals from case to case, which can be useful to improve the detection accuracy in special cases, cannot be seen on the normalized spectrum. Thus, the absolute spectrum needs to be used. Simulations have been performed to illustrate the benefit of using absolute spectrum to distinguish the vital signs that can not be identified in normalized spectrum.

In simulation, a state with normal respiratory strength is set as follows: the amplitude of respiratory signal is much larger than heartbeat and heart rate is faster than respiratory rate (RR=60, HR=80, m_r=0.8 mm, m_h=0.2 mm). In another state, a much weaker respiratory signal at 80 and normal strength heartbeat signal at 60 (RR=80, HR=60, m_r=0.4 mm, m_h=0.2 mm) was used. Fig. 9 shows the comparison of absolute spectrums of these two states set as above.

It can be observed from Fig. 9 that under normal conditions (the dash line), there is always an evident strong signal on the spectrum, which indicates the strength of normal respiratory signal. Since the amplitude of respiratory signal is always larger than that of heartbeat, even when breathing becomes weaker, its amplitude is still larger than heartbeat. Therefore, the highest peak on the absolute spectrum usually represents the respiratory signal. If the peak of an absolute spectrum drops to a lower level, as shown in Fig. 9 (solid line), it can be determined that the respiration of the infant becomes weak. If using normalized spectrum, since this variation of signal strength cannot be seen from the spectrum, the ill infant may still be considered to be normal, thus missing the opportunity of instant treatment due to misdiagnosis.

Although it can be initially diagnosed from the spectrum

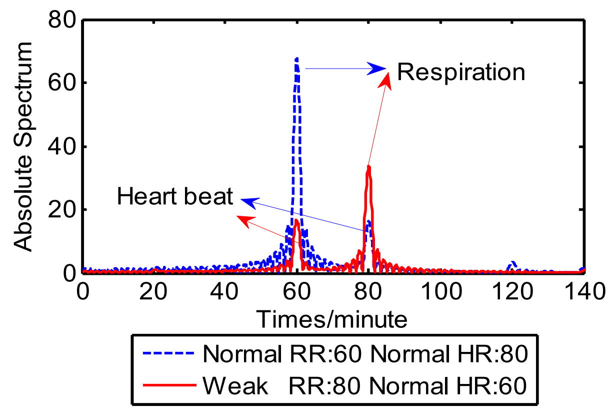


Fig. 9. The comparison of simulated absolute spectrums of two cases. Case1: Normal RR at 60, normal HR at 80. Case2: Weak RR at 80, normal HR at 60.

shown in solid line in Fig. 9 that the infant breathing becomes weaker, it still cannot distinguish which signal is respiration and which is heartbeat. However, it is known that the amplitude of heartbeat has a relatively narrow varying range, which is from 0 mm (no heartbeat) to 0.3 mm (very strong heartbeat). Using calibration or nonlinear phase modulation effect [6] can potentially obtain the accurate vital sign movement amplitude. If the amplitude is larger than 0.3 mm, it can be determined as respiratory signal, not heartbeat. In this approach, the vital signs can be correctly identified.

IV. CONCLUSION

For the first time, the accuracy of a non-contact Doppler radar vital sign monitoring system was verified by an infant simulator. The experimental results show that the system can track the variations of vital signs of some typical syndromes. Limited by hardware and algorithm, the system could not detect vital signs accurately in some abnormal cases. It is suggested that direct coupling circuit, carrier frequency tuning technique, and further spectral analysis can be used to improve the detection accuracy in those special cases. In summary, the experimental results demonstrated the potential of using Doppler radar sensor for non-contact monitoring of sleeping infants to reduce SIDS.

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