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Article

A Noncontact Vital Signs (NCVS) System for Potential Patient Monitoring Enabled by Robust Software Defined Radio (SDR)

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Abstract: This research proposes a robust non-contact vital signs (NCVS) sensor system for continuously monitoring the human respiration rate (RR) and heart rate (HR) within a distance of 1 to 2 meters. The novel Doppler-based NCVS sensor system is realized using an SDR (software defined radio) unit with optimized transmit/receive gain in commercial broadband, which filters intermediate frequency (IF) and operates at 2.4 GHz ISM band using a pair of small antennas. When compared with the vital signs data measured by traditional contact-based sensors, the NCVS sensing system demonstrates excellent accuracy in real-time RR/HR monitoring within 0.5/3 BPM (breath/beat per minute). We have obtained an IRB (Internal Review Board) approval to start a small clinical trial at Texas Tech University Health Sciences Center (TTUHSC) soon, hoping to use this system to effectively monitor vital signs of COVID-19 patients and to help telehealth delivery in the post-COVID-19 era.

Keywords: Biosensor, Intermediate Frequency (IF), Non-contact Vital Signs (NCVS), Respiration Rate (RR), Software Defined Radio (SDR)

1. Introduction

Software defined radio (SDR) is a technology with great potential, as traditional hardware components in a radio system are mostly implemented in wideband integrated circuits (ICs) that are controlled and reconfigured by software, and can be operated on a personal computer (PC) or in an embedded system with field-programmable gate array (FPGA) [1-3]. Many key functions previously delegated to hardware such as filtering, mixing, and demodulation are now handled in an SDR by digital signal processing (DSP) in a chip or by a microcontroller with DSP-friendly instructions. We have recently reported a prototype Doppler-based RADAR system for non-contact vital signs (NCVS) monitoring by using an SDR technology based on National Instruments (NI) Universal Software Radio Peripheral (USRP)-2901 and LabView programming [4,5]. A pair of commercially available PCB (printed circuit board) Log Periodic Dipole Antenna (LPDA) with a gain of 6 dBi at 2.4 GHz, a bandwidth of 0.9−2.6 GHz, and a size of 13x15 cm are used in the system owing to their good directivity, low cost, and small size [6]. The previously reported SDR-enabled prototype NCVS system in Ref. [4] has demonstrated that it monitors a subject's respiration rate (RR) up to the distance of 180 cm with the same relative accuracy when using the 2.4 GHz continuous wave (CW) signal for both the transmit (TX) and receive (RX) mode in a zero intermediate frequency (IF) radio architecture (i.e., homodyne). However, the received waveforms in the in-phase and quadrature (I/Q) channels are often noisy, such that the monitored vital signs, especially the smaller heart rate (HR) signals are not significantly reliable. Therefore, in this research, we have improved the previous NCVS system by using a low-IF radio architecture with the same NI-USPR 2901 hardware and demonstrated much cleaner I/Q channel waveforms with more accurate and consistent RR/HR data compared to the prototype reported in Ref. [4]. In addition, since most of the hardware settings are now easily controlled by software using the SDR technology, the result of this research shows the low-IF SDR-enabled NCVS system achieves robust real-time HR/RR monitoring by optimizing the TX/ RX gain and IF frequency settings. The NCVS system allows robust remote vital signs monitoring on HR with an error rate of less than 3 BPM, and especially with accurate respiration rate (error rate less than 0.5 BPM). Impressive NCVS monitoring results on multiple volunteers provides various potential clinical applications on patients.

2. Materials and Methods

The NCVS system and its setup are shown in Figs. 1−3. The SDR technology used in this research is based on National Instruments (NI) Universal Software Radio Peripheral (USRP)-2901 and LabView programming [5,6]. Figure 1 shows the NI USRP-2901 SDR box with its two ports connected to the antennas at the RF0's "TX1 RX1" port and the RF1's "TX1 RX1" port. When the SDR is turned on, the TX port has its red light turned on, while the RX port has its green light turned on. This SDR box weighs only 676 g with dimensions of 12.5×9.4×3.8 cm (L×W×H). The detailed operational principle of the Doppler-based NCVS system is described in Ref. [7]. As the NCVS system operates in a continuous-wave (CW) mode where both the TX and RX channels are simultaneously on and continuously transmitting/receiving at 2.4 GHz in a full-duplex mode without using an isolator. Then, a homodyne receiver radio architecture directly downconverts the phase-modulated signal from periodic chest movements of the reflected TX signal that inevitably suffer from 1/f noise and DC offset issues [8]. We implement a simple DC offset algorithm in LabView to calibrate the system static DC offset. However, due to the intrinsic 1/f noise of the transceiver IC used in the NI USRP-2901 and downconverted vital signs signals of low frequencies close to DC (i.e. HR/RR are from 0.15 to 3 Hz), the zero-IF direct downconversion RX architecture is susceptible to 1/f noise. A higher IF selection provides the system with a lower 1/f noise. However, since the USRP-2901 has a maximum I/Q rate of 15 MS/s. When considering the laptop's hardware constraint to stably operate the proposed system, the RX I/Q rate is set at 144 KS/s for the 2-channel system. In this case, the maximum IF is 144 kHz divided by 2, which is at 72 kHz, but such a high IF selection becomes an obvious overkill for ADC sampling of vital signs signals at less than 3 Hz and consumes more power. In this case, the IF selection needs to be optimized. In addition, all of the TX and RX gain settings are fixed at 34 and 45, respectively in this research. Measurements were taken on seven volunteers of different heights (1.6 to 1.9 m), body weight (60 to 80 kg), and genders, while they were seated at 1.3 m away from the antennas' tips of the NCVS system (Fig. 3).

Fig. 1. The NI USRP-2901 SDR hardware in the proposed NCVS system.

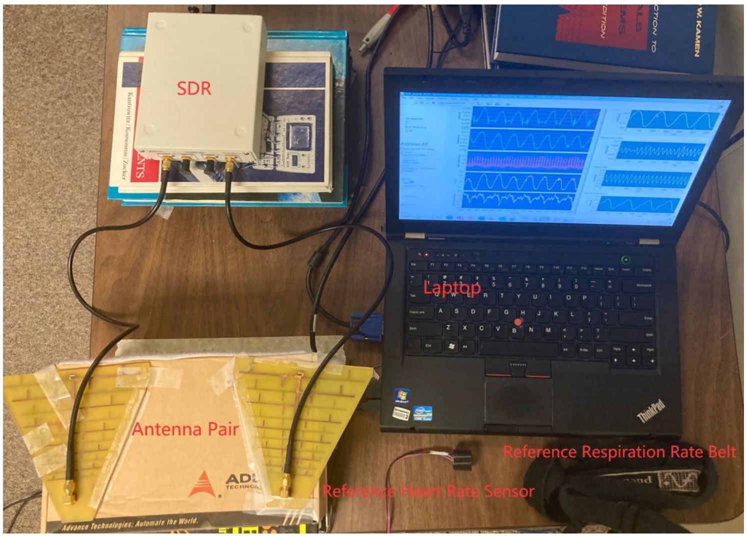

Fig. 2. The hardware required for the proposed NCVS system: an antenna pair, a NI USRP SDR box, and a laptop.

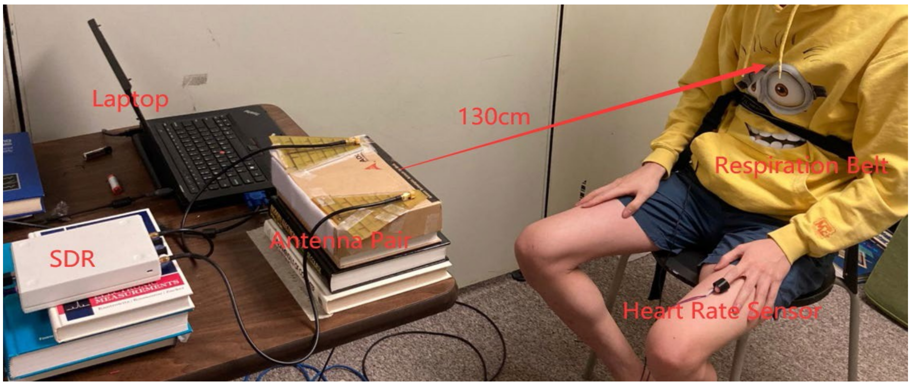

Fig. 3. The SDR-enabled NCVS system test setup in our lab on a student volunteer.

3. Results

The measured vital signs data using the SDR-enabled NCVS system is shown in this section. The HR and RR are compared with the vital signs measured by traditional contact-based sensors by synchronizing their waveforms.

3.1. NCVS System Measured I/Q/Arctan Waveforms and HR/RR

Figure 4 shows the measured waveforms of the I-channel, Q-channel, and the Arctan modulated waveforms for the proposed NCVS system using a zero-IF setup [4] with all of the TX and RX gain settings fixed at 34 and 45, respectively. The I-channel waveform is rather noisy which results in a noisy Arctan waveform and BPM of a high error on measured HR/RR over 10 sessions as shown in Fig. 5 (especially on the HR). The figure shows that the vital signs from both traditional contact-based sensors and those from the CVS sensors are tracked and compared with the boxplots that show the BPM distribution error. As Figs. 6 and 7 clearly illustrate, increasing the IF to 1 kHz improves the quality of waveforms considerably and reduces the measured errors of the NCVS system. It is worth noting from the boxplots that the measured RR tracks the reference signal within 0.5 BPM in 23 measurement sessions, which is most likely owing to the significant reduction in 1/f noise. However, when the IF is increased to a high frequency such as 70 kHz as shown in Fig. 8, unpredictable DC issues show up in all waveforms, which affects the system's ability to produce accurate RR/HR rate. As the result of the IF optimization process, the proposed NCVS system produced clear waveforms with robust vital signs data at IF=1 kHz.

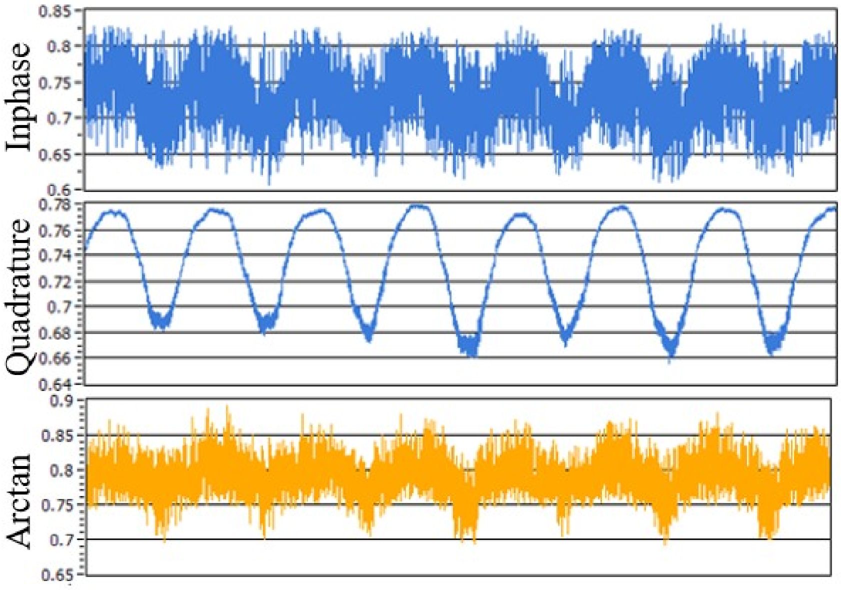

Fig. 4. Examples of NCVS measured I/Q and Arctan waveforms at IF= 0 Hz (i.e., homodyne RX).

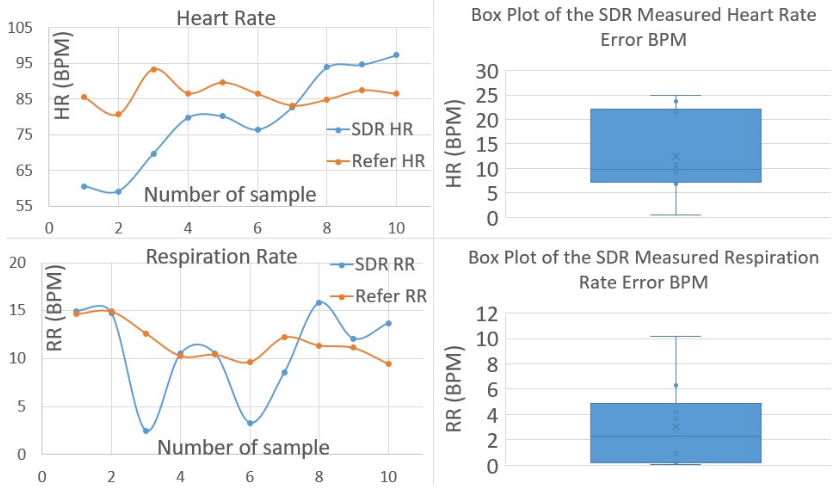

Fig. 5. The vital signs measured by the NCVS system at IF = 0 Hz vs. reference signals across 10 cases (left), and boxplots of the statistics of errors from these 10 cases (right).

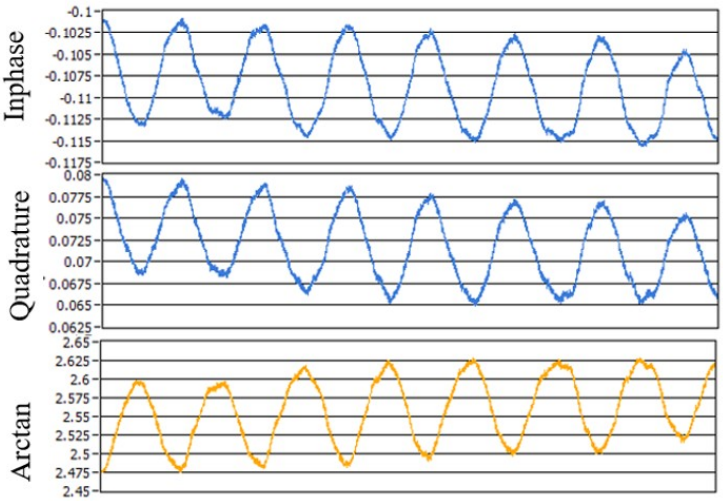

Fig. 6. Examples of NCVS measured I/Q and Arctan waveforms at IF=1kHz.

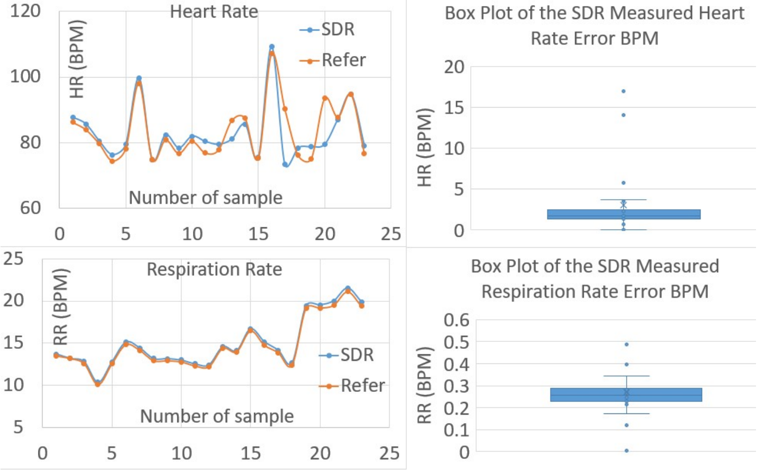

Fig. 7. Vital signs measured by the NCVS system at IF = 1 kHz vs. reference signals across 23 cases (left), and boxplots of the statistics of errors from these 23 cases (right).

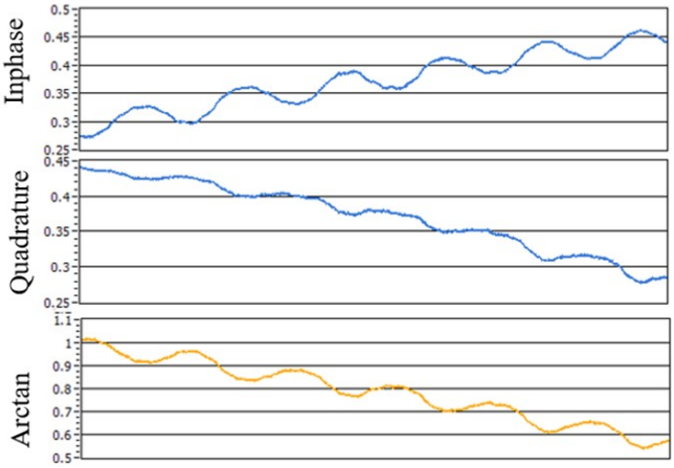

Fig. 8. Examples of NCVS measured I/Q and Arctan waveforms at IF=70 kHz.

3.2. *TX/RX GAIN OPTIMIZATION*

TX/RX gain setting is another important factor that significantly affects the system's performance. If the TX/RX gain combination is "mismatched", that is, TX gain is too high and RX gain is too low, or TX gain is too low and RX gain is too high, the signal waveforms become noisy and/or distorted, which makes the measured HR/RR inaccurate compared to the reference data. In this research, the NI SDR transmitter box had a gain step of 0.25 dB, with an output power range from -3 dBm (TX=1) to 20 dBm (TX=89), while the receiver had a gain step of 1 dB and a gain range of 76 dB [5]. An example of the optimization of the TX/RX gains for a fixed TX=21 (i.e., +3 dBm) is presented here, where RX gain is optimized for the low-IF NCVS system.

Figures 9 and 10 show that at TX=21, setting the RX gain to 69 was too high for the test setup. Lowering RX gain to 45 improved the waveforms and data quality considerably (Figs. 11 and 12). In the case of TX=21 and RX=69, since a significantly higher power was amplified through the SDR box than in the case of RX=45 (24 dB), considerable signal distortions occurred and caused the ADC to incorrectly digitize the I/Q waveforms, which degraded the measured data accuracy. Furthermore, once the RX gain setting was lowered to 21, the system began to suffer from degraded SNR. This was observed in some of the channel waveforms which became noisy (Fig. 13), but the HR/RR accuracies still looked acceptable (Fig. 14). If the RX gain was further lowered to 18, all I/Q/Arctan channel waveforms became noisier (data not shown). Therefore, we conclude from this TX/RX gain optimization process that the RX gain setting needs to stay within 45 to 21 in the case of TX=21 (i.e., +3 dBm) for the low-IF NCVS system used in the setup as shown in Fig. 2.

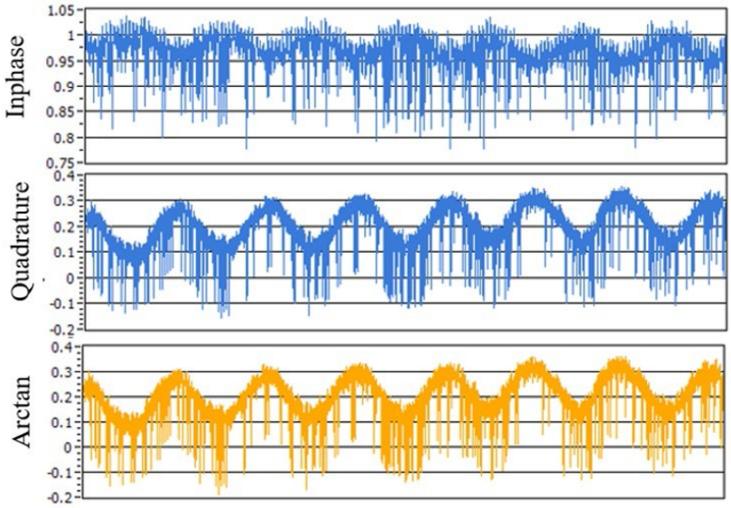

Fig. 9. Examples of NCVS measured I/Q and Arctan waveforms at RX=69 (TX=21, IF=1 kHz).

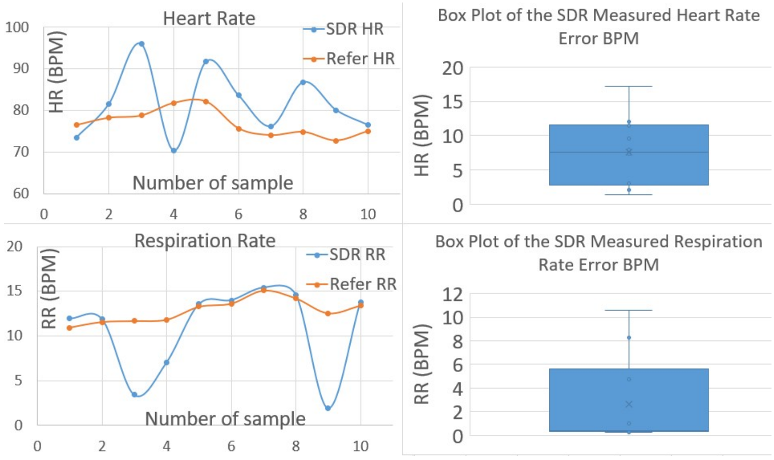

Fig. 10. Analysis of vital signs measured by the NCVS system at RX=69 (TX=21, IF=1 kHz) vs. reference signals across 10 cases (left), and boxplots of the statistics of errors from these 10 cases (right).

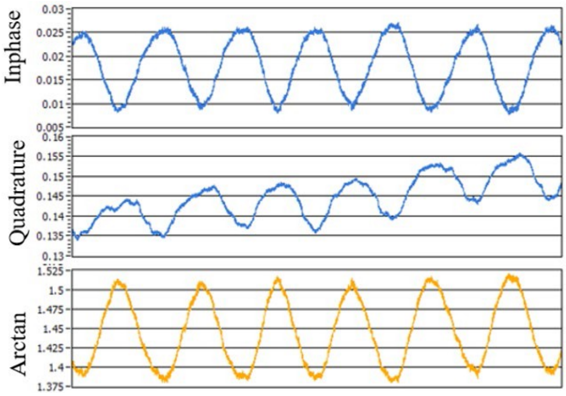

Fig. 11. Examples of NCVS measured I/Q and Arctan waveforms at RX=45 (TX=21, IF=1 kHz).

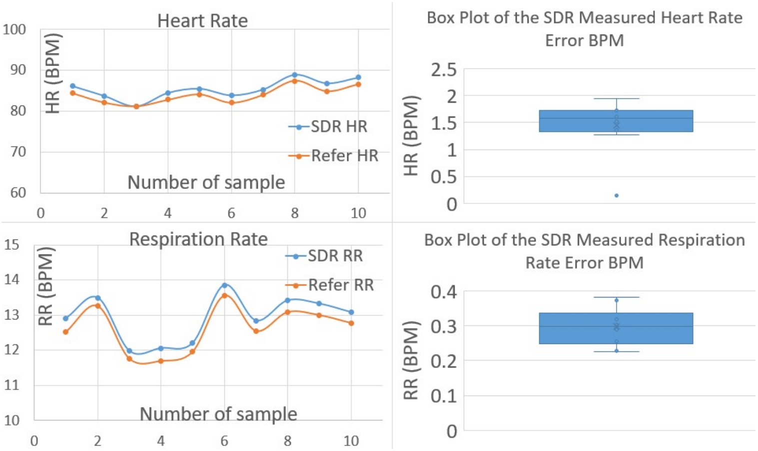

Fig. 12. Analysis of vital signs measured by the NCVS system at RX=45 (TX=21, IF=1 kHz) vs. reference signals across 10 cases (left), and boxplots of the statistics of errors from these 10 cases (right).

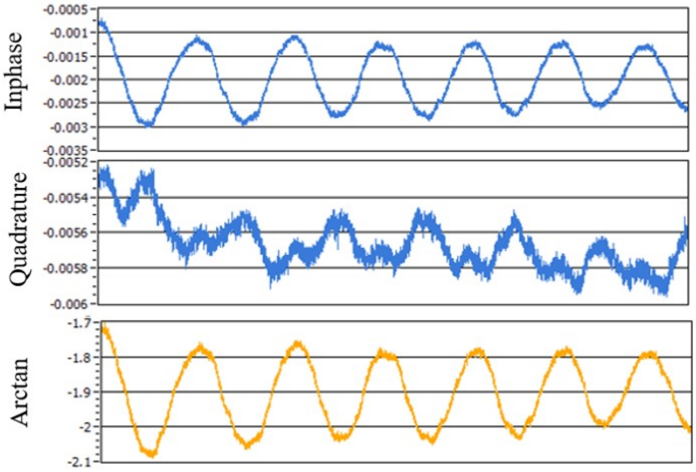

Fig. 13. Examples of NCVS measured I/Q and Arctan waveforms at RX=21 (TX= 21, IF=1 kHz).

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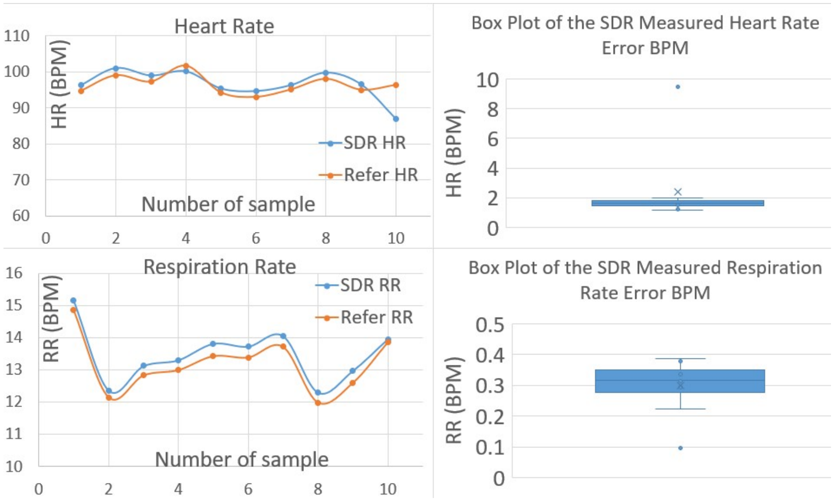

Fig. 14. Analysis of vital signs measured by our NCVS system at RX=21 (TX=21, IF=1 kHz) vs. reference signals across 10 cases (left), and boxplots of the statistics of errors from these 10 cases (right).

4. Discussion

As COVID-19 is highly contagious and the confirmed cases already surpassed 35.6 millions with over 628,000 deaths in the US alone as of July 30, 2021, many hospitals have been severely overburdened and taking strict safety measures. The lack of proper personal protection equipment (PPE) and the inevitable donning-and-doffing errors often make the healthcare workers (HCW) particularly vulnerable to be infected by the SARS-CoV-2 virus. Monitoring patients' vital signs is essential but requires close patient contact during its setup and adjustment, and the high PPE consumption rate forces HCWs to reuse masks, which places HCW at higher risks to COVID-19. We aim to minimize the clinician-patient contacts by proposing a new NCVS sensor replacing the traditional contact-based vital signs monitoring sensors. The proposed NCVS sensor is placed on a desk for telemedicine use, or hopefully located by a bed for continuous vital signs monitoring. This continuous NCVS monitoring system is particularly useful for checking patients' respiration rates who are not admitted in the ICU yet but suspected as COVID-19 patients in general hospital wards, quarantine hotels, or at home. The system is expected to benefit from active and continuous RR monitoring to detect rapid breathing to prevent "happy hypoxia" or rapid disease progression from happening. Thus, the NCVS system reduces the chances of cross-infection of HCW-patient considerably and serves as an effective means for wireless-acute-care, where the system alerts the clinicians on the shortness of breath of patients (e.g., if RR increases to above 24 BPM). It is now well-known that patients with COVID-19 increase respiratory rate at hospital admission have suffered from markedly elevates the risk for mortality [9].

It is currently a tedious task working on the TX/RX gain pair optimization/selection since we have to manually change and test different gain settings. However, two measurement criteria need to be followed: (1) the waveforms on all I/Q/Arctan channels need to be clean, which means the waveforms do not have any obvious noise/distortion issues, and (2) accurate output HR/RR data with errors less than 3/1 BPM when compared to the reference signals. We plan to implement an AGC (automatic gain control) loop in the system so that the TX/RX gain pair calibration process is automatically carried out. For testing in the lab setting, the measured data of the optimization process of the TX/RX gain pair indicates that the RX gain setting needs to be within 12 to 45 for any TX setting between 21 and 45. In an actual clinical setting, the optimized TX/RX gain setting may be different, depending on the room size and the distance of the NCVS system to monitored patients. The NCVS system has a user-friendly graphic user interface (GUI) for easy control of the SDR, and NCVS data extraction and processing is rather straightforward based on a user manual of the NCVS system.

The system is the world's first SDR-based low-IF continuous NCVS monitoring system that has gone through an IRB approval for clinical evaluation on real patients. The preliminary experimental results on volunteers validated the attractiveness and feasibility of the NCVS system for potential clinical and telemedicine applications. The boxplots of the measured RR showed that the results were significantly close to the reference signals (within 0.5 BPM across 30 measurement sessions), which indicates the high accuracy of the system with optimized settings (on IF frequency, TX/RX gain pair, etc.)

5. Conclusions

This research aims to provide a novel robust low-IF SDR-enabled NCVS system, with validates vital signs monitoring accuracy on multiple student volunteers and for many monitoring sessions. The system demonstrates the optimized IF selection and the RX/TX gain settings. When compared to the low-IF NCVS system to the prototype zero-IF system reported in Ref. [4], this system is more accurate, with real-time RR and HR remote monitoring accuracy within 0.5/3 BPM, respectively. In addition, the optimization process helps to obtain clean I/Q/Arctan waveforms and provides a wide process window for the system to operate within. The measured waveforms and HR/RR data with error statistics also provide insights into the roles of 1/f noise, distortion, and radio architecture selection on an SDR-abled NCVS system performance. The robust HR/RR monitoring data is applied for an IRB approval to start a small clinical trial at the Physician's Clinic for remote monitoring of real patients' vital signs at the Dept. of Otolaryngology at Texas Tech University Health Sciences Center (TTUHSC). The trial has been approved, and the personnel has been under training to conduct this trial properly. We hope to use our system to benefit patients by close monitoring and get rid of the stress of nursing staff at ICU. ER, and so on. It reduces the risk of patients' and staff's frequent exposures with the traditional contact-based monitoring sensors (for COVID-19, burns, bone marrow transplant, etc.) We believe such a system can keep the healthcare providers safer, and patients better monitored and treated than before. Additionally, it also benefits at-home monitoring and telehealth delivery in the post-COVID-19 era.

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Conflicts of Interest: The authors declare no conflict of interest.

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