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Contactless Human Vital Sign Monitoring System Using Millimeter Wave FMCW Radar for Healthcare Applications

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***Abstract*—During the COVID-19 pandemic, the need for contactless monitoring of people became very clear. To prevent the spread of the virus, physical interactions were minimized. As a result, many industries, including healthcare, are now focusing on touchless solutions. This research is driven by the need to tackle significant healthcare issues caused by contagious diseases, limited resources, and a shortage of healthcare workers. The paper discusses designing a contactless vital sign monitoring device that uses a 60 GHz FMCW radar and a thermal sensor to track respiratory rate, heart rate, and skin temperature. Heart sufferers and the elderly will benefit most from this device. It is appropriate for usage during sleep and in situations of viral illnesses due to its contactless nature. The device uses a thermal sensor to assess temperature and a 60 GHz radar to track heart rate and respiration rate. An Arduino 33 IoT processes data from the radar before sending it to display. For the age group 22 to 25, the device detected the heart rate accuracy of approximately 92.11% and a respiratory rate accuracy of about 89.88%. For the age group 45 to 79, the device shows a heart rate accuracy of around 96.05% and a respiratory rate accuracy of approximately 93.73%. These accuracy rates were determined from 90 data samples from 18 participants, with the accuracy derived from their Mean Absolute Percentage Error (MAPE%) values.**

Keywords*—*Vital Sign, Contactless Monitoring, Heart Rate, Respiratory Rate, Skin Temperature, FMCW, IoMT, mmWave, Radar Antenna, Healthcare

I. INTRODUCTION

The evolution of ubiquitous sensing has led to millimeter-wave frequency modulated continuous waves in short FMCW radar technologies, while FMCW radars are widely utilized in automotive, industrial, and medical domains, their unique features make them suitable for contactless human vital sign detection. Generally, there are four types primary vital signs: body temperature, blood pressure, respiratory rate, and heart rate. Any abnormal changes in vital signs have become an active area of concern that can be early indicators of a patient’s deterioration and adverse events. This research’s primary aim is to develop a contactless human vital sign monitoring system utilizing mm-wave FMCW radar for healthcare applications. This research work stems from the challenges faced by healthcare professionals during the COVID-19 pandemic in measuring vital signs through traditional methods, such as attaching probes to patients. This approach is uncomfortable for patients and increases the risk of healthcare staff contracting the virus. To address these issues, our project focuses on radar-based technology for non-intrusive and contactless human vital sign monitoring. The anticipated outcomes of this research are assured to significantly contribute to innovative solutions in eldercare and safety monitoring, particularly for patients with arrhythmia. The inclusion of a digital interface facilitates chip configuration and radar data acquisition. Additionally, the sensor incorporates optimized power modes to ensure efficient low-power operation, and it comes equipped with an integrated state machine, enabling independent operation. This sensor holds promise across various applications. Certainly, employing FMCW radar for contactless vital sign detection encounters challenges in scenarios with multiple targets, such as objects or other individuals. The radar system may face difficulties in distinguishing between the specific individual's heart rate and respiratory rate and the movements of other nearby objects or people. This challenge has the potential to impact the accuracy and precision of the vital sign algorithm, utilizing millimeter-wave FMCW radar for vital sign detection aims to eliminate the discomfort associated with continuous monitoring of heart rate and respiratory rate in elderly, newborn, or unwell patients, which is notably high when using probes attached to their bodies.

This research was conducted at the Center for Biomedical Research (CBR), Dr. Anwarul Abedin Institute of Innovation (D2A2I), AIUB.

II. LITERATURE REVIEW

An FMCW radar is a sensor that uses frequency modification and observes the change of the subject range, angle, and velocity simultaneously. FMCW radar depends on the concept of the Doppler effect. The Doppler effect is a phenomenon that is observed when the source of the waves changes its distance [1]. With FMCW technology one can detect vital signs easily. Vital signs are now measured by ECG, breathing sensor, and others which is a costly solution and needs contacts of the patients and expert operators to operate them. Radar based systems can do it contactless and cost-effectively. Fadel Adib et al.[2] tested radar transmitting signals sweeping from 5.46 GHz to 7.25 GHz every 2.5 milliseconds. the device demonstrated a median accuracy of 99% for breathing and heart rate monitoring and also can monitor vital signs from up to 8 meters or even from behind a wall. Alizdeh et al.[3] investigated the respiratory rate and heart rate by 77 GHz After collecting data found 94 % accuracy was found for breathing and 80 % for heart rate.

Wang et al.[4] used a 77 GHz mm-wave FMCW radar for heart rate and breathing rate measurement and found 93% accurate. Giulia Sacco et al.[5] proposed a system working in the 5.8 GHz ISM band. The experimental results show the accuracy of heart rate independently with maximum error in terms of BPM is 0.8 BPM and 3.1 BPM for the respiratory and heart rate, accordingly. Leem et al.[6] developed a 6.8 GHz IR-UWB radar-based system using the NVA6201 transceiver to monitor vital signs and detect mobile phone use for car crash prevention. Placed under the steering wheel, the system achieved nearly 100% accuracy in detecting phone usage, even during stationary, general movement, and driving conditions. Fuchuan Du et al.[7]developed an algorithm for multi-target vital sign extraction using a 60 GHz FMCW radar. The approach includes noise filtering with the DC offset method, separation of breathing and heartbeat using Empirical Mode Decomposition, and multi-target monitoring via an L-shaped antenna. However, limitations in detection range, transmission power, and antenna count challenge the algorithm's ability to accurately position and distinguish between multiple individuals. Yaokun Hu et al.[8] monitors vital signs of multiple moving targets for heart rate estimation was 4.09 bpm, with an accuracy of 95.88%. Turppa et al.[9] monitored vital signs with a 24 GHz FMCW radar in different scenarios. After comparing with traditional Embla titanium portable polysomnography system and ECG they got an accuracy of 91% for respiratory rate and 96% for heart rate. Xiang et al.[10] proposed a system with 77 GHz radar and found 98.67% accuracy for respiratory rate and 98.04% for heart rate. Choi et al.[11] proposed a method to improve the heart rate measurement efficiency by FMCW radar. The authors used temporal phase coherency with the gathered data. Arsalan et al.[12] enhanced contactless heartbeat estimation using a 60 GHz BGT60TR13C radar and a Kalman Filter Tracking method, achieving root-mean-square errors of 5.3 bpm and 7.0 bpm, significantly reducing errors by a factor of 3 compared to previous methods (17.6 bpm and 21.3 bpm). The proposed method had the lowest MD, -1.02 BPM with a 95% confidence interval of -8.33/6.30 BPM whereas other methods have around comparable mean differences but with wider confidence intervals, indicating greater variability in their results.

III. Methodology

The developed device utilizes an FMCW radar which transmits a sinusoidal wave called chirp whose frequency increases linearly with time. Utilizing FMCW radar and an IR thermal camera module alongside Arduino 33 IoT, the project is built to efficiently transmit real-time human vital signs such as heart rate, respiratory rate, and body temperature to the device's output display as mentioned in the working block diagram Fig. 1.

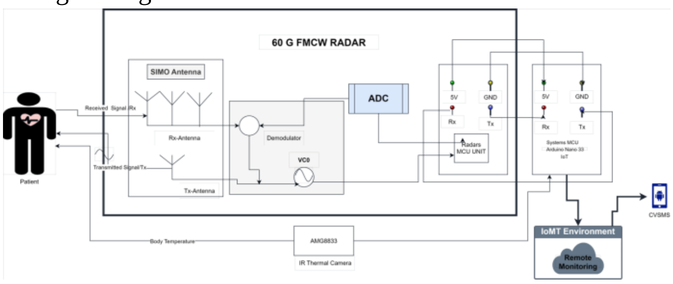

Fig. 1. Working block diagram of the contactless vital sign monitoring system.

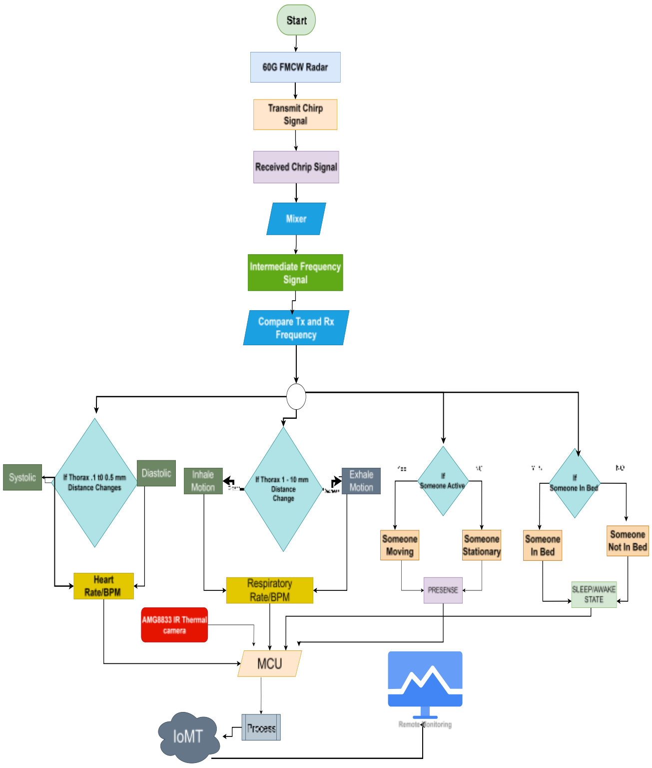

Fig. 2. Flowchart of the contactless vital sign monitoring system.

Fig. 2. explains the flowchart of the working principle of the device where the main component is 60Ghz band millimeter wave FMCW radar. Our particular radar has a transmitter antenna and two receiving antennas. The transmitter transmits a 60Ghz band millimeter wave signal and the measured target reflects the electromagnetic wave signal demodulates the transmitted signal and processes it through amplification, filtering, and phase of the eco-signal data. Then the data is sent to the microcontroller unit in a small MCU unit. In our case for measuring breathing and heart rate the system relies on the observation that when an individual inhales, their chest expands, bringing it closer to the antenna. Conversely, during exhalation, the person's chest contracts, moving away from the antenna, which increases the distance between the chest and the antenna and prolongs the reflection time. The MCU unit then calculated the amplitude, frequency, and phase of the eco-signal and measured the targeted parameter heart rhythm and respiratory rate. To measure body temperature, an IR thermal camera module (Model no. AMG8833) is connected to a microcontroller unit (MCU). This setup allows for the accurate measurement of human body temperature. Finally, the MCU unit sends ta data to MATLAB's cloud service ThingSpeak, and from the ThingSpeak Server the data is pulled down to the developed Android app CVSMS Which shows the real-time results.

A. Simulation (MATLAB)

To analyze the FMCW radar system, a MATLAB simulation was performed which transmitted and received the IF signal and visualized the result and spectrogram which helps to understand the radar signal behavior in different scenarios and can proceed to extract information like distance and velocity. The radar system sets basic parameters, starting with the bandwidth (B) for fine range resolution, calculated using the desired resolution and speed of light, followed by the chirp time (T_{chirp}) based on maximum detection range, ensuring adequate round-trip time for signals. The chirp slope is the rate of frequency change over time, derived from bandwidth and chirp time. Maximum and current intermediate frequencies (f_{IFmax} and f_{IF}) correspond to beat frequencies for the maximum and current ranges. Speed resolution (vr_{es}) determines the smallest detectable velocity change, influenced by light speed, carrier frequency, chirp count, chirp time, and an additional time parameter, with sampling rate (Fs) based on ADC samples and chirp time. The transmitted signal (Tx) is a chirped cosine wave with a linearly varying frequency. The received signal (Rx) reflects this signal's delayed return, indicating target distance and motion. The intermediate frequency (IF) signal, representing the difference between transmitted and received frequencies, helps ascertain the target range. Fast Fourier Transform (FFT) analyzes the IF signal's frequency components, providing Doppler and range information. The spectrogram with time change visualizes frequency variations over time, aiding in detecting target displacements and velocities via phase changes. Key radar parameters, including maximum range, resolution, carrier frequency, and others, guide this process, ultimately enabling accurate measurement of target distance and speed as mentioned in the following equations (1), (2), (3), (4), (5), (6), and (7).

$$Tx = \cos(2\pi . angle_{freq}) \tag{1}$$

$$x = \cos(2\pi \left(f_c(t - t_d) + \frac{slope(t-t_d)^2}{2} \right)) \tag{2}$$

$$IFangle_{freq} = f_c . t + \frac{slope . t^2}{2} - (f_c . (t - t_d) + \frac{slope . (t-t_d)^2}{2} \tag{3}$$

$$IFx = \cos(-2\pi(f_c(t - t_d) + \frac{slope(t-t_d)^2}{2} 2\pi . angle_{freq}) \tag{4}$$

$$IFx = \cos(-2\pi(f_c(t - t_d) + \frac{slope(t-t_d)^2}{2} 2\pi . angle_{freq}) \tag{5}$$

$$doppler = 10 . \log_{10}(|fft . (IFx(1{:}1024))|) \tag{6}$$

$$frequency = fftshift(\left(\frac{-N_r}{2} : \frac{N_r}{2} - 1\right) . \left(\frac{F_s}{N_r}\right)) \tag{7}$$

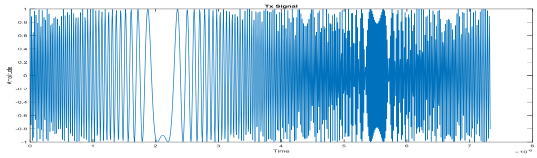

Fig. 3. Tx Wave from of the MATLAB Simulation

Fig. 3 represents the angular frequency of the transmitted signal, incorporating the carrier frequency and the frequency modulation over time due to the chirp slope. The transmitted signal Tx is a cosine wave with the calculated angular frequency.

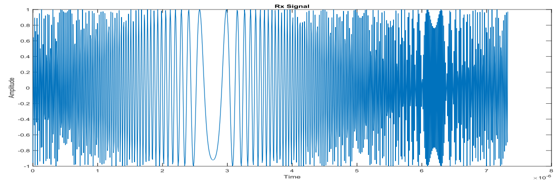

Fig. 4. Rx Wave from of the MATLAB Simulation.

Fig.4. represents received signal, the frequency of the received signal increase linearly over time due to the slope. The received signal Rx is a cosine wave with the angular frequency considering the time delay td.

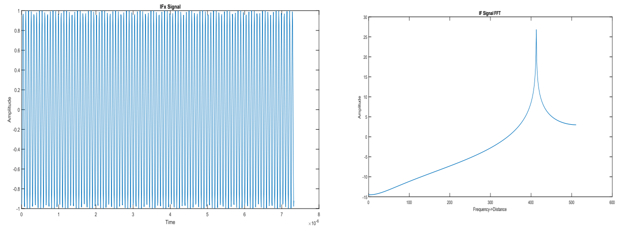

Fig. 5. IF Signal and FFT of IF signal.

Fig.5. representing the angular frequency difference between the transmitted the received signal which corresponds to the beat frequency and the fft generate the frequency axis for the FFT result shifted to center around zero. Which is calculated form the frequency axis of the FFT result, using the speed of light and the chirp slope which translates the frequency components into distance measurements.

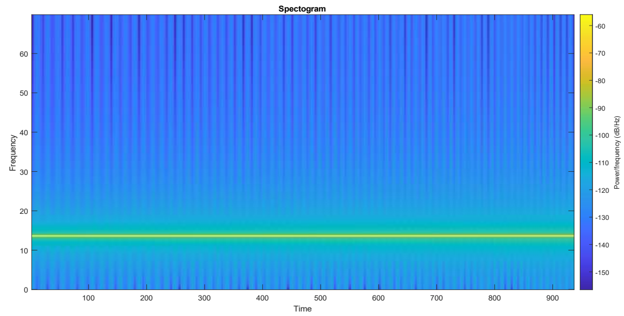

Fig. 6. Spectogram of FMCW the MATLAB Simulation

Fig.6. explains that the IF signal frequency change due to target displacement within a single FRAME cycle which is difficult to distinguish within the spectrogram, so for detection of small displacements and velocities can be done by phase changes.

B. Hardware Implepentation

The 60 GHZ radar and the AMG8833 thermal sensor are connected to the MCU. The RX pin of the radar sensor is connected to the TX pin of the MCU and the Tx of the radar is connected to the Rx pin of the MCU and shows the data on the screen to D1 and D2 screen. The AMG 8266 is also connected with the D1 and D2 pins of the node-MCU. The radar, Screen, and thermal sensor are powered from Arduino 33 IoT and a 9V adapter. The system should keep aligned with the chest of the patient for more accurate data collection.

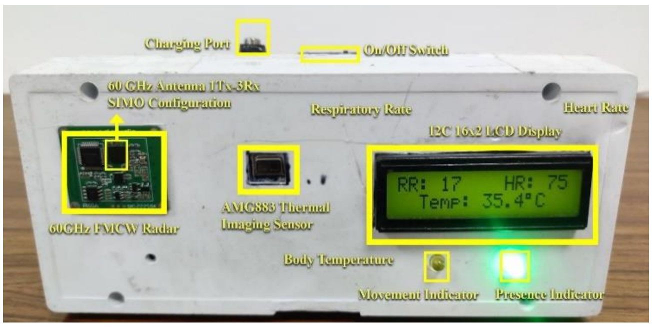

Fig. 7. Device prototype for contactless vital sign monitoring(CVSMS)

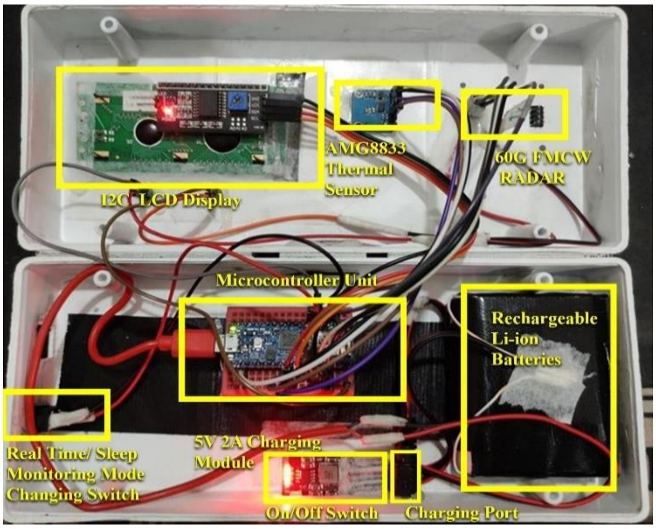

Fig. 8. Device prototype inside view of contactless vital sign monitoring(CVSMS).

For lying patients, the system can be set in a PVC pipe structure and aligned with the chest. The radar will collect data of the patient and show it. Also can be send it to the attendant or nurse through IoMT service. By which the attendant can monitor the patient. To power the entire system, a battery pack with a BMS is used. The battery pack ensures portability of the system. The sensor setup to be deployed in various locations without relying on a constant external power source.

IV. Result Analysis

The Ethical Review Board of American International University-Bangladesh (AIUB), following the Declaration of Helsinki, provided ethical approval for the experiment. The test involved 10 volunteers in the 22 to 25 age range, equally divided between 5 male and 5 female students, as well as 8 volunteers aged 40 to 79, including 5 males and 3 females. None of the participants reported any notable respiratory illnesses.

Table I. consists of 10 volunteers heart rate and respiratory rate taken from radar and their reference values by conventional elements. The MAPE percentage of each individual participant and for all the percipients are also presented on the table. The MAPE for heart rate and respiratory rate is 7.89% and 10.12%, respectively, indicating a comparatively higher error. Accuracy for respiratory rate is 89.88% and 92.11% for heart rate. The lower accuracy in respiratory rate is due to fractional respiration values not being accurately counted.

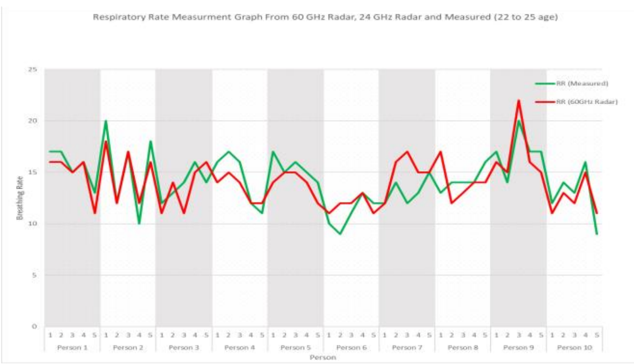

Fig. 9. Respiratory rate data for measured vs radar data(Age 22 to 25)

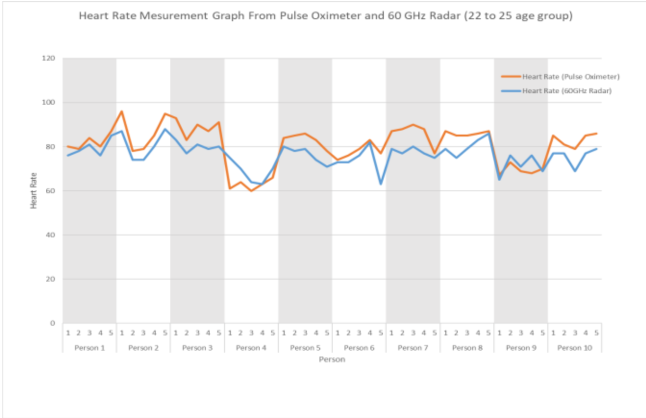

Fig. 10. Heart rate data for measured vs radar data(Age 22 to 25)

Table II. consists of 8-person data age range 40 to 79. The data table indicates that the MAPE for individual measurements is generally low, with most values under 9%, suggesting that the Radar R60A readings are closely aligned with the PO readings. The overall MAPE for heart rate and respiratory rate measurements stands at 3.95% and 6.27%, respectively. For the age group 45 to 79, the device shows a heart rate accuracy of around 96.05% and a respiratory rate accuracy of approximately 93.73%. Each person's heart rate results vary slightly depending on the measurement. This could be related to a number of variables, including exercise level, stress, or time of day. From 2 data table analysis it can be said that the device is more effective for aged people. As the heart rate is comparatively low for the aged people so comparing with young people so the device can detect the measurement easily. The breathing rate MAPE is also low comparing with young people. So the device is more compatible for elderly people.

Fig. 11. Respiratory rate data for measured vs radar data (Age 40 to 79)

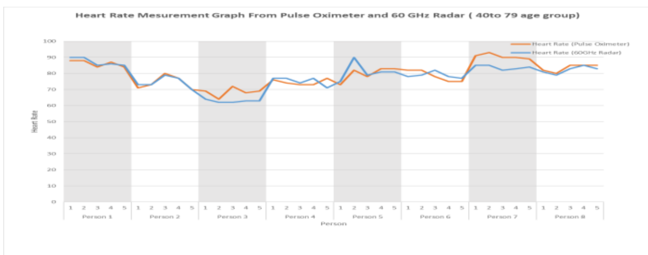

Fig. 12. Heart rate data for measured vs radar data (Age 40 to 79).

TABLE I. DATA TABLE FOR AGE VARIATION 22 TO 25 YEARS OLD

Subject	Gender	Age	BMI	Heart Rate (PO)	Heart Rate (Radar R60A)	MAPE% (Individual)	MAPE% (OVERALL)	RR (Calculated)	RR (Radar R60A)	MAPE% (Individual)	MAPE % (Overall)
1	M	25	33.15	80, 79, 84, 80, 87	76, 78, 81, 76, 85	3.43	7.89	17, 17, 15, 16, 13	16, 16, 15, 16, 11	5.43	10.12
2	F	24	19.57	96, 78, 79, 85, 95	87, 74, 74, 80, 88	6.82		20, 12, 17, 10, 18	18, 12, 17, 12, 16	8.22	
3	M	24	24.81	93, 83, 90, 94, 91	83, 77, 81, 78, 80	11.42		12, 13, 14, 16, 14	11, 14, 11, 15, 16	11.60	
4	F	22	26.21	61, 64, 60, 63, 66	75, 70, 64, 63, 70	9.01		16, 17, 16, 12, 11	14, 15, 14, 12, 12	9.17	
5	M	24	29.50	84, 85, 90, 83, 78	80, 78, 70, 74, 71	11.01		17, 15, 16, 15, 14	14, 15, 15, 14, 12	8.97	
6	F	24	32.17	74, 76, 79, 83, 77	73, 73, 76, 82, 63	5.70		10, 9, 11, 13, 12	11, 12, 12, 13, 11	12.15	
7	M	24	25.55	91, 88, 90, 88, 77	74, 77, 80, 77, 75	11.48		12, 14, 12, 13, 15	12, 16, 17, 15, 15	14.27	
8	F	23	24.16	87, 85, 85, 86, 87	79, 75, 79, 83, 86	6.53		13, 14, 14, 14, 16	17, 12, 13, 14, 14	12.94	
9	M	22	21.19	67, 73, 69, 68, 70	65, 76, 71, 76, 69	4.64		17, 14, 20, 17, 17	16, 15, 22, 16, 15	8.13	
10	F	22	19.68	85, 81, 79, 85, 86	77, 77, 69, 77, 79	8.91		12, 14, 13, 16, 9	11, 13, 12, 15, 11	10.33	

TABLE II. DATA TABLE FOR AGE VARIATION 40 TO 79 YEARS OLD

Subject	Gender	Age	BMI	Heart Rate (PO)	Heart Rate (Radar R60A)	MAPE% (Individual)	MAPE% (OVERALL)	RR (Calculated)	RR (Radar R60A)	MAPE% (Individual)	MAPE % (Overall)
11		50	27.68	88, 88, 84, 87, 84	90, 90, 85, 86, 85	1.61	3.95	20, 22, 18, 17, 18	18, 21, 17, 16, 16	7.41	6.27
12		62	23.36	71, 73, 80, 77, 76	73, 73, 79, 77, 76	0.81		16, 12, 13, 12, 15	15, 13, 12, 12, 14	5.78	
13		79	25.03	69, 64, 72, 68, 69	64, 62, 62, 63, 63	8.06		12, 13, 12, 16, 14	11, 12, 12, 15, 15	5.88	
14		51	21.28	76, 74, 73, 73, 77	77, 77, 74, 77, 71	4.01		12, 13, 15, 16, 16	11, 12, 16, 16, 17	5.78	
15		56	26.28	79, 82, 78, 83, 83	75, 90, 79, 81, 81	4.18		20, 21, 21, 21, 19	17, 21, 19, 18, 18	8.81	
16		45	32.17	82, 82, 78, 75, 75	78, 79, 82, 78, 77	4.07		10, 09, 11, 13, 12	10, 09, 12, 13, 11	3.48	
17		56	26.28	91, 93, 90, 90, 89	85, 85, 82, 83, 84	7.49		20, 21, 20, 21, 19	19, 20, 16, 19, 18	8.90	
18		40	27.04	82, 80, 85, 85, 85	81, 79, 83, 84, 83	1.61		15, 16, 13, 12, 11	14, 15, 12, 12, 11	4.12	

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V. Conclusion

The developed contactless vital sign detection technology, utilizing a 60 GHz FMCW radar, has demonstrated promising results in monitoring heart rate and other vital signs. The system has been rigorously tested, with data collected from a diverse sample of young and older volunteers. For the younger population, aged between 22 to 25 years, the percentage of error was recorded at 7.89% for heart rate and 10.12% for respiratory rate. In contrast, the older volunteer group exhibited a Mean Absolute Percentage Error (MAPE%) of 3.95% and 6.27% for heart rate and respiratory rate, respectively. These results highlight the system's robustness and its potential for accurately monitoring vital signs across different age groups. The lower error rates observed in the older population suggest that the technology may be particularly beneficial for elder care, where continuous and accurate monitoring is crucial. Looking forward, the development of an Android application could significantly enhance the utility of this technology. By integrating this system into a non-invasive, real-time remote patient monitoring framework within an IoMT (Internet of Medical Things) environment, healthcare providers could gain seamless access to patient data. This would not only facilitate more proactive and personalized care but also pave the way for future innovations in remote health monitoring. Such advancements could revolutionize patient care, making it more accessible and efficient to all classes of the population.

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