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Evaluation of a Doppler radar sensor system for vital signs detection and activity monitoring in a radio-frequency shielded room



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ABSTRACT

This study presents an evaluation of an advanced Doppler radar-based method for detection of vital signs, presence, and activity of a human subject in a test room with radar-signal reflecting aluminum-coated surfaces. Ten test subjects lay in four positions, and they sat in two locations in the room, both breathing normally and holding their breath. The mean ratios of the pulse rates determined from the radar signal and electrocardiography and respiration reference signals were 110% (respiration) and 99% (heartbeat), and the mean occupied and empty room radar signal variance ratios were 608 (breathing) and 20 (breath-hold). In a one-subject activity monitoring test, walking, standing and lying activities could be well separated from the radar signal. The results are promising and the proposed system seems to have potential to be used in position-independent health and activity monitoring of, for example, elderly people in care homes or intoxicated people in police custody.

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1. Introduction

Reliable contactless monitoring of vital signs is needed in many healthcare and medical surveillance applications. Radar-based detection can be utilized in emergency situations to find buried or hiding people [1–4]. Contactless monitoring of vital signs is also needed when attaching, e.g., ECG electrodes is not advisable due to burnt skin [4] or the possibility of exposing nursing staff to toxic materials [5]. A contactless radar-based detection system can also provide a cost effective and versatile method to monitor the vital signs of sleeping elderly in care homes or intoxicated people in police custody [6].

This study presents an evaluation of an advanced contactless Doppler radar-based system for detecting the vital signs of a human subject. To enable a comprehensive room-scale field of view and good reflections of the radar signal, the radar sensor is installed in the upper corner of an aluminum-coated radio-frequency-shielded test room in a tilted position. Using a human-sized metallic chamber for improving radar-based vital signs monitoring has been previously tested by Chen et al. [4]. To the authors' best knowledge, however, this is the first time the method is applied to a room-like setup. The configuration of the presented detection system is described, and its performance for vital signs detection and activity monitoring is evaluated using ten test subjects in several positions and locations in the test room. A small-scale general activity monitoring test with one test subject and different activity types is also carried out. Expanding the functions of the detection system to presence and activity monitoring diversifies remarkably its use and choice of applications.

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2. Materials and methods

2.1. Ethics statement

This study was conducted according to the principles expressed in the Declaration of Helsinki. The Research Ethics Committee of Aalto University stated that, since ethical approval, as stated in the Finnish Medical Research Act and as required by the National Advisory Board on Research Ethics in Finland, is necessary only for medical research, this study needs not undergo an ethical review, especially in the view that the integrity of the test subjects was not endangered in any way. The ethical principles of research in the humanities and social and behavioral sciences followed in Finland are available in [7]. The contents of the test and the course of its events were explained before-hand to each test subject individually, and written consent was received from each of them.

2.2. Radar sensor

A continuous-wave microwave Doppler radar sensor was assembled for the test setup (Fig. 1). The basic principle is that the Doppler radar signal reflected from the monitored subject is phase modulated by the subject's respiration and heartbeat [8], which allows the detection of vital signs. The test radar was implemented using waveguide technology, which may also improve the detection of vital signs by filtering off the sub-harmonics of the radar signal [9].

The transmitter of the radar uses an M/A-COM 4000-series Gunn diode oscillator at the single frequency of 34 GHz. The maximum power of the radar is 100 mW, but in the test setup it is operated at 10 mW. The radar signal's wavelength λ is about 9 mm, which is of the same order as the chest deviation due to respiration (4–12 mm) and is not too large compared that due to heartbeat (0.2–0.5 mm) [10]. The millimeter-level wavelength also enables the use of a relatively small-sized antenna. In the test radar, a horn antenna was used for its good directivity.

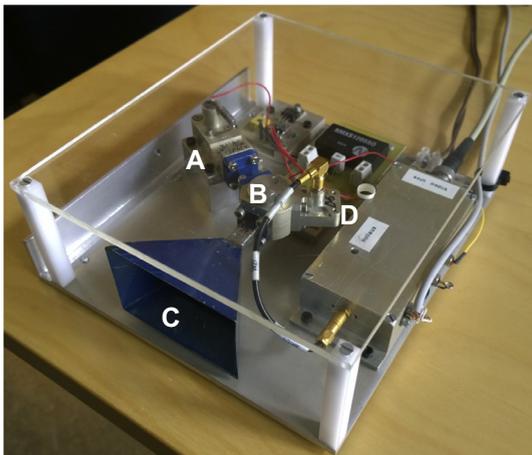


Fig. 1. Radar sensor used in the test setup. The main parts of the sensor are the transmitter (A), circulator (B), horn antenna (C) and, receiver and amplifier (D).

The receiver of the radar sensor employs one-diode phase detection to find the Doppler frequency of the reflected signal. The transmitter and antenna are connected to the receiver through a ferromagnetic waveguide circulator (Fig. 1). The circulator leaks the transmitted signal also to the receiver, where it is mixed with the reflected signal. The difference of these two signals is then phase detected. Due to the Gunn diode's temperature dependence, there is always some noise and drift present in this systems. In this prototype version, a multi-turn potentiometer was used to trim the radar output signal offset. The power density of the radar is far lower than the recommended safety limits in Finland for nonionizing radiation [11].

2.3. Test room

A test room having dimensions of 205 cm \times 120 cm \times 195 cm (length \times width \times height) was constructed of 30-mm (walls and door) and 50-mm (floor and ceiling) thick polyurethane insulation boards with 0.2-mm aluminum coating on both-sides (Fig. 2). The floor was coated with an additional 7-mm laminate-panel covering enabling movements of the test subject inside the room. While not reflecting the dimensions of a regular room, the room comfortably accommodated one person in different positions and allowed walking inside. To improve test subject comfort, a camping mattress made of 190T polyester with polyurethane foam and air filling of size 183 cm \times 51 cm \times 2.5 cm was placed in the middle of the test room. Ventilation of the test room was realized with two wall-mounted fans. The radar sensor was placed on a shelf in the corner near the ceiling of the room. The radar's antenna was at a height of about 173 cm from the test-room floor, and it was directed downwards vertically at a 33° angle and horizontally at 45° angles to the walls.

2.4. Radio-frequency shielding of the test room

Aluminum reduces the absorption of the radar signal in the building materials and guarantees maximum reflections of the signal [12]. Along with the tilted installation of the radar sensor, the aluminum coating was used to facilitate the best possible radar signal reflections and coverage in the test room.

2.5. Reference measurements and data acquisition

Reference measurements were performed to obtain direct information on the respiratory efforts and heartbeat of the test subjects. Electrocardiography (ECG) signal was measured with a wireless ECG monitor (BioNomadix BN-EKG2, BIOPAC Systems, Goleta, CA, USA) using the bipolar limb lead II. The respiratory efforts were detected with a wireless respiration monitor (BioNomadix BN-RESP-XDCR, BIOPAC Systems, Goleta, CA, USA) placed on the test subject's abdomen. All signals were recorded with commercial data acquisition hardware and PC software (MP150 and AcqKnowledge 4.3, BIOPAC Systems, Goleta, CA, USA) at a sampling rate of 1000 samples/second. The radar sensor was coupled to the data acquisition system



Fig. 2. Radio-frequency shielded test room. The entrance to the test room (left), and an internal view of it (right). The radar sensor (A) is placed in the test-room corner in a pointing downwards position.

through a universal interface module (UIM100C, BIOPAC Systems, Goleta, CA, USA).

2.6. Test subject protocol

Ten male volunteers with an average age of 33 years (standard deviation, SD 8.5 years), average weight of 79.5 kg (SD 14.9 kg), and average height of 175.2 cm (SD 7.1 cm) were measured as test subjects. For every test subject the test session took about one hour.

The evaluation recordings were made with each test subject in four different lying positions (supine, prone, right side and left side) and two sitting positions. In the lying positions, each test subject lay on a mattress in the center of the test room with his head facing the rear wall of the room. The sitting position was performed both under the radar and in the opposite corner of the room. In each position, measurement data was first acquired for two minutes with the test subject breathing normally. After this, the test subject was instructed to take a deep breath and hold his breath for as long as he felt comfortable. An empty test room was also measured with the radar sensor for two minutes as a reference along with each test subject measurement.

An additional test with one of test subjects (S1) was carried out. The subject walked clockwise in a circle in the test room, stood still (facing the wall with the door), sat in the middle of the floor (legs and torso straight), and lay in the supine position, as described before, both breathing normally and holding his breath. Additionally, the radar signal of the empty test room was measured both with the test room ventilation fans on and off. All of these conditions were measured with the radar sensor for 20 s. No breathing or ECG measurements were made during this test.

2.7. Signal processing and data analysis

The radar signals captured during the breath-hold included visible periods of deep inhalation and exhalation

that were cut off from the data prior to analysis. Artefacts due to hand-adjusting the temperature drift cancellation potentiometer and obvious test-subject-originated artefacts were also manually removed from the measurements. No samples were removed from the middle of a measurement but also the data before or after the artefact—whichever was shorter in duration—was cut off.

The radar signal was filtered using a finite impulse response (FIR) band-pass filter (BPF) with a -92 -dB Blackman window. The pass-bands used were 0.1–10 Hz and 0.5–15 Hz in the normal breathing and breath-hold measurements, respectively. The corresponding empty room measurement data was filtered similarly using the same pass bands. Due to good signal quality, the acquired reference respiration signal was not filtered. The ECG signal was high-pass filtered (HPF) using a FIR filter with a cut-off frequency of 0.5 Hz and a -92 -dB Blackman window. For the radar signal that was acquired in the short general activity monitoring test, a FIR BPF with a -92 -dB Blackman window and a pass-band of 0.5–10 Hz was used.

The periodicity of respiration and heartbeat signals can be derived by calculating their autocorrelation [13]. The values of breathing pulses per minute (PPM) and heartbeats per minute (BPM) were calculated as the mean distance between the peaks in the computed autocorrelation function. The positive and negative lags in the autocorrelation function were restricted to 30 s (respiration) or 3 s (heartbeat). In addition, the results were manually checked from the filtered signals and clearly false results were excluded from following analyses. For evaluation of the accuracy of the radar-based results, the ratio of the values determined from the radar and the reference signals was calculated for each measurement.

The possibility to use the system as a presence monitor was evaluated by computing variances of the radar signals of each measurement. After this, the ratios of the variances of the occupied and test subject-specific empty-room radar signals were calculated.

3. Results

Out of the 60 normal breathing and breath-hold radar measurements, 22 (37%) and 60 (100%), respectively, had to be cut due to some kind of artefact. In the empty room measurements, the number of cut measurements was 6 out of 10 (60%). The average durations of the usable radar signal measurements were as follows: normal breathing cases 108 s (SD 19.8 s), breath-hold cases 29 s (SD 15.3 s), and empty room cases 98 s (SD 26.5 s).

In the case of normal breathing, a total of 43 measurements (72%) and in the case of breath-hold 52 measurements (87%) out of 60 were visually judged as adequate to be used in the analysis. Examples of interpretable and uninterpretable radar-detected respiration and heartbeat signals are presented in Figs. 3 and 4, respectively. The average respiration and heartbeat rates determined from the radar signal are plotted as a function of the corresponding reference measurements in Fig. 5. The linear trend lines in Fig. 5 have correlation coefficients of $R = 0.840$ (Fig. 5a) and $R = 0.929$ (Fig. 5b). The subject- and position-specific ratios are presented for the respiration rates in Table 1

and for the heartbeat rates in Table 2. The minimum, average, and maximum values of the ratios of respiration and heartbeat rates determined from the radar and reference signals of the whole test subject group for each subject position are presented in Fig. 6. The mean values of measurements in every test subject position are 110% and 99% in the normal breathing and breath-hold cases, respectively.

The minimum, average, and maximum values of the radar signal variance ratios of an occupied and empty test room for the whole test subject group for each subject position are presented in Fig. 7. During normal breathing, the variance ratio between the occupied and the empty test room was at least 17.6 for each subject. During the breath-hold periods, the ratio was at least 2 in 82% of the measurement. The overall mean occupied and empty room variance ratios were 608 and 20 in the normal breathing and breath-hold cases, respectively.

The ratios of variance of the empty room and filtered radar signal during different activities are presented in Fig. 8. The movement artefacts that are visible in the upper plot of Fig. 8 between the breath-hold and empty room

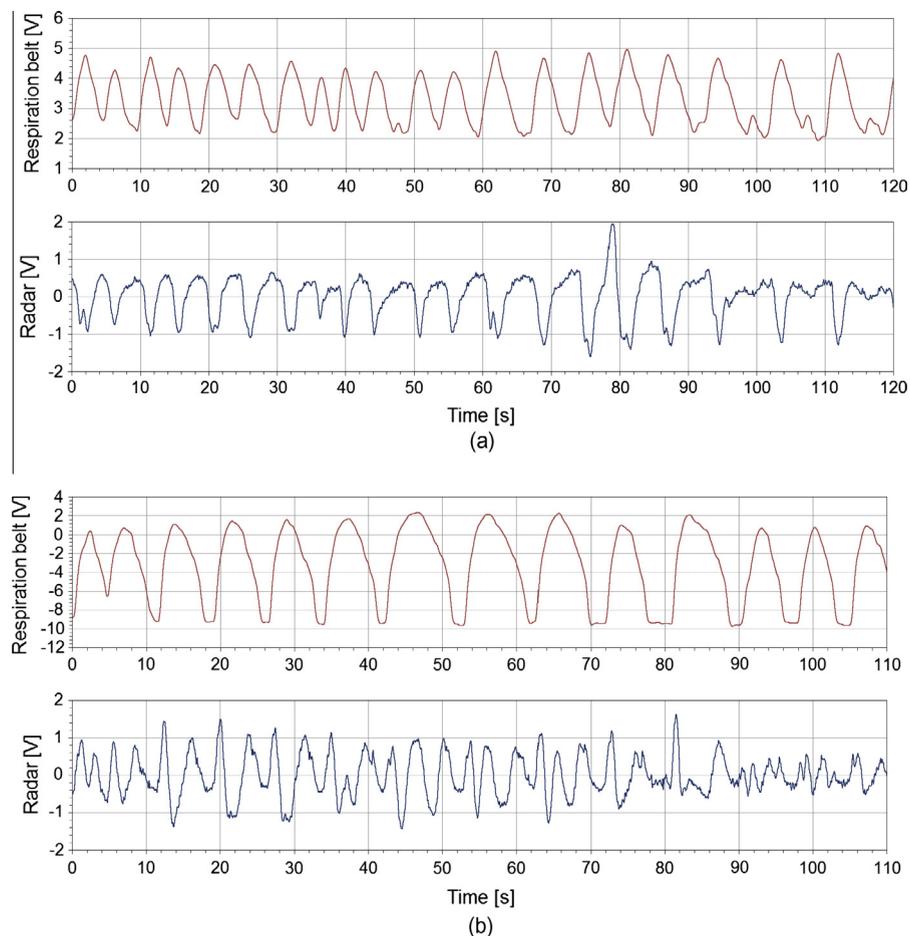


Fig. 3. Example results of the normal breathing periods. The subfigures show interpretable (a) and uninterpretable (b) radar-detected respiration signals. (a) Represents the supine and (b) the left side position of the same subject. Depending on the radar signal reflections, the reference and radar sensor signals can be in same or opposite phases. In (a), the signals are in opposite phases.

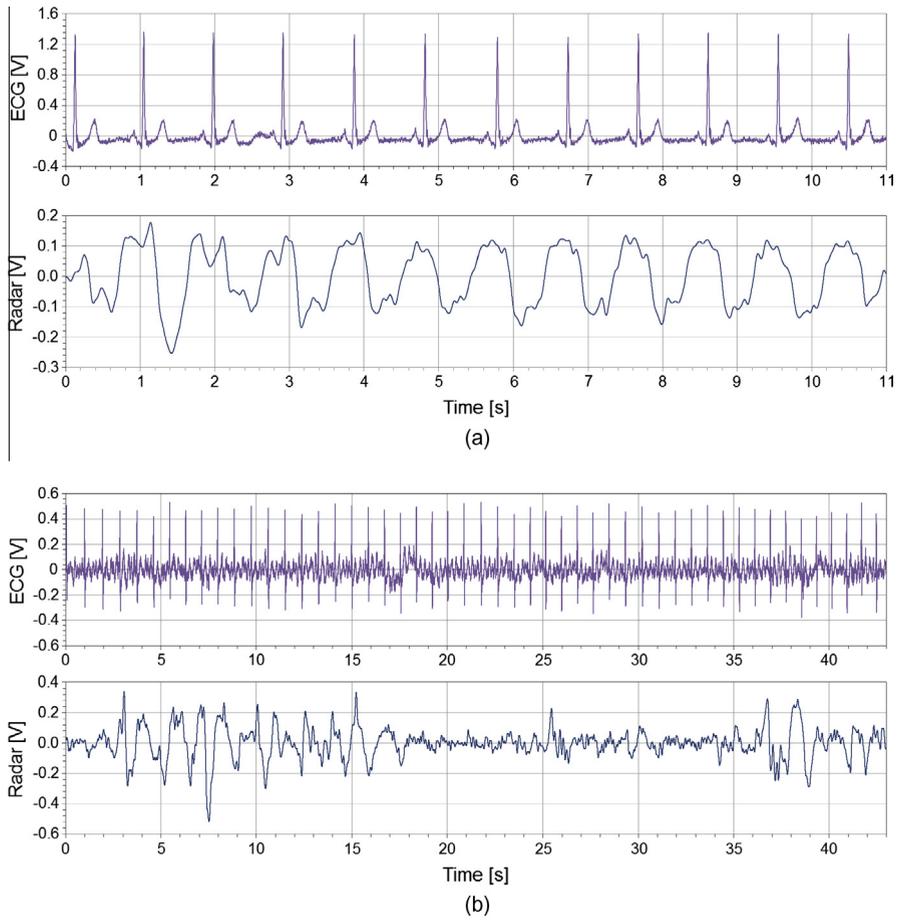


Fig. 4. Example results of the breath-hold periods. The subfigures show interpretable (a) and uninterpretable (b) radar-detected heartbeat signals. (a) Represents the left side and (b) the opposite-to-radar sitting position of different subjects.

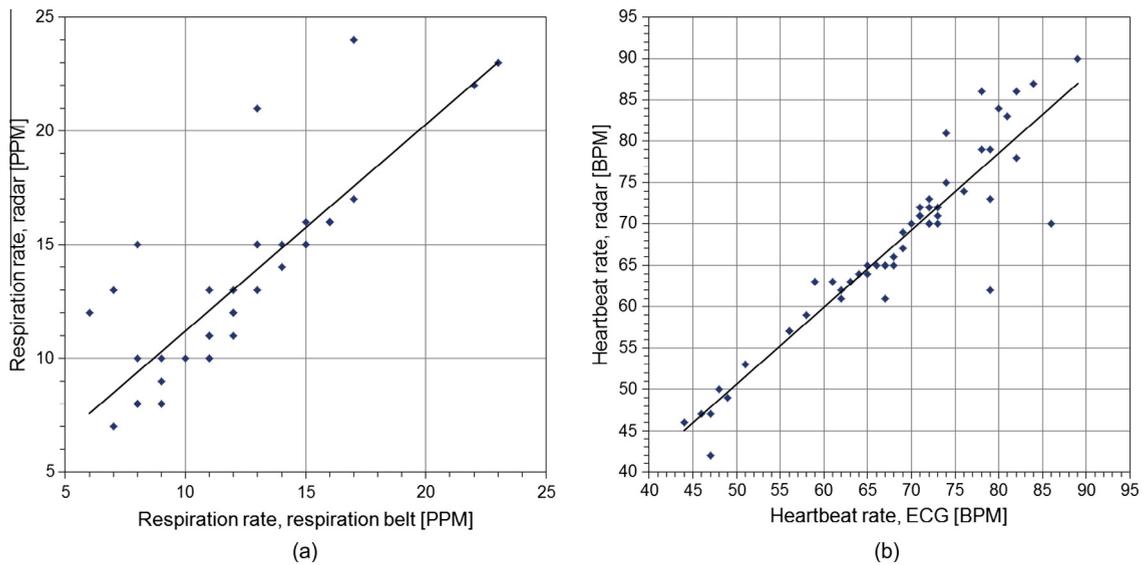


Fig. 5. Respiration and heart rates. The subfigures represent the average values determined from the reference and radar signals in normal breathing (a) and breath-hold (b) cases (marked with diamonds). The linear trend lines are drawn in solid color. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1

Test subject- and position-specific respiration rate ratios. The values represent the ratio of the radar-based and the reference signal. S1–S10 indicate the test subject number.

Position	S1 (%)	S2 (%)	S3 (%)	S4 (%)	S5 (%)	S6 (%)	S7 (%)	S8 (%)	S9 (%)	S10 (%)
Supine	125	100	FAIL	100	100	100	100	FAIL	111	115
Left side	FAIL	100	FAIL	100	FAIL	107	115	FAIL	FAIL	162
Right side	89	100	186	100	92	100	100	100	100	FAIL
Prone	100	107	FAIL	200	100	100	118	FAIL	188	100
Sitting opposite the radar	108	141	100	89	115	100	FAIL	91	100	100
Sitting under the radar	100	100	FAIL	FAIL	100	FAIL	FAIL	FAIL	91	FAIL

Table 2

Test subject- and position-specific heartbeat rate ratios. The heartbeat rate ratios were detected from the breath-hold period measurements. The values represent the ratio of the radar-based and the reference signal. S1–S10 indicate the test subject number.

Position	S1 (%)	S2 (%)	S3 (%)	S4 (%)	S5 (%)	S6 (%)	S7 (%)	S8 (%)	S9 (%)	S10 (%)
Supine	89	97	101	91	105	98	97	101	97	102
Left side	100	102	101	92	97	100	100	95	98	102
Right side	104	103	100	100	97	98	100	100	96	100
Prone	105	102	102	101	FAIL	97	100	FAIL	FAIL	104
Sitting opposite the radar	FAIL	78	FAIL	101	97	109	97	81	110	100
Sitting under the radar	FAIL	105	FAIL	96	100	99	100	FAIL	104	107

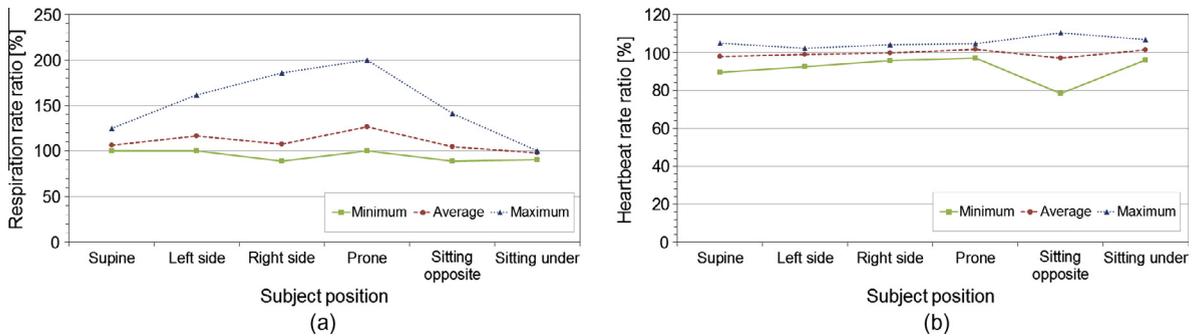


Fig. 6. Ratios of respiration and heartbeat rates determined from the radar and reference signals. The subfigures represent the minimum, average and maximum values of the test subject group for each subject position in normal breathing (a) and breath-hold (b) cases.

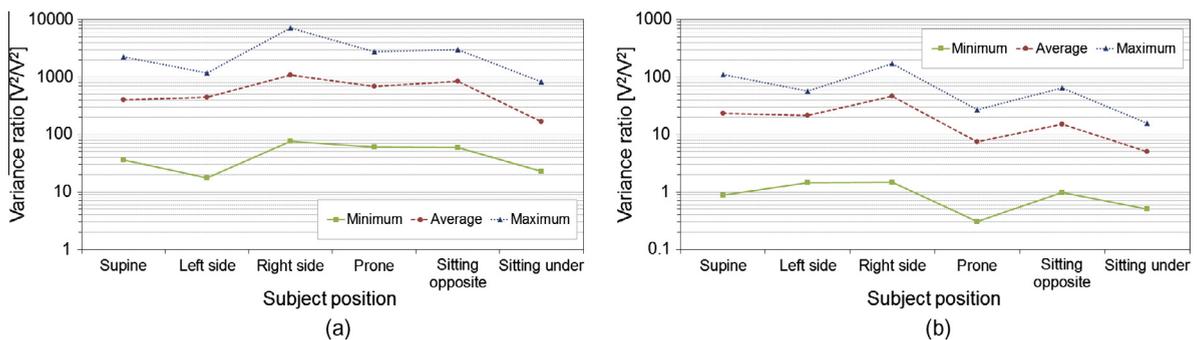


Fig. 7. Radar signal variance ratios of an occupied and empty test room. The subfigures represent the minimum, average and maximum values of the test subject group for each subject position in normal breathing (a) and breath-hold (b) cases. Note the logarithmic vertical scales.

cases, and between the empty and fans off cases were cut off before computing the corresponding variances.

4. Discussion

The results of the vital signs detection show that during normal breathing the pulse rate determination method

seems to overestimate the results more than during breath-hold (Fig. 6). The results also have more deviation during normal breathing (Fig. 5). The correlation of the radar-derived respiration signal and reference respiration signal is strong (0.84 and 0.93 for normal breathing and breath hold, respectively). In the work of Li et al. [9], the best accuracy of vital signs detection was achieved when

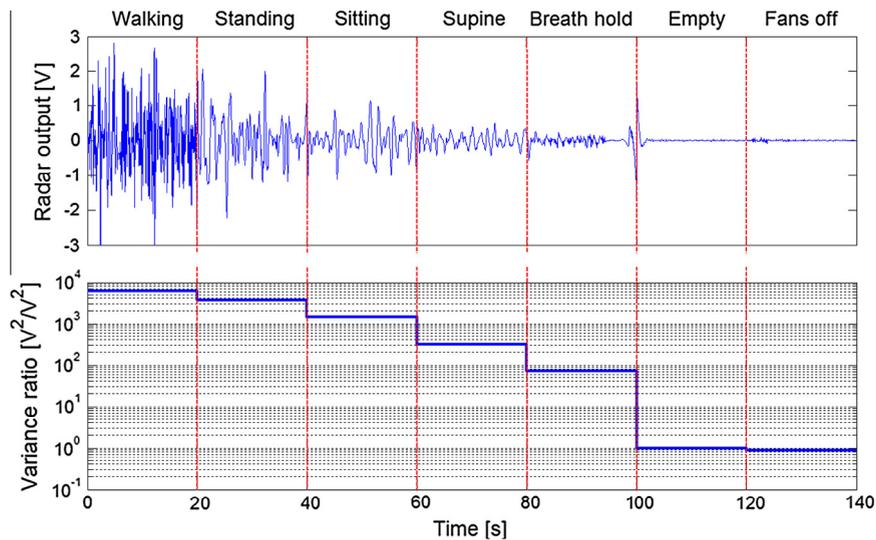


Fig. 8. Radar output and corresponding activity-empty room variance ratios. Note the logarithmic vertical scale in the lower plot.

measuring from the back of the body, and in the work of Chen et al. [4] the cardiac activity and respiration signals of test subjects could be clearly detected in the supine and side positions. In the present study, the most optimal position for detection varied from subject to subject. This was probably due to different physique of the test subjects and possible difficulties to stay still in different position.

Not all of the measurements were good enough to be used for respiration- and heartbeat-rate detection (Tables 1 and 2). In the case of normal breathing, there was at least one measurement in the results of all but one test subject that could not be used. In the case of test subjects S3 and S8, respiration detection results in four positions out of six of had to be discarded. These two subjects were the heaviest test subjects, and the only who weighted over 100 kg. Thus, it is possible that the robust physique of them—including weight, body composition, movement of body when breathing, and possible tremor originating from physical instability—complicated the respiration detection. In the breath-hold case, only five subjects had bad measurements. In the normal breathing cases there were discarded measurements in every subject position, but mostly in the left-side and sitting-under positions. Thus, none of the positions in general was significantly superior or inferior compared to others in terms of ease for respiration detection. In the breath-hold case, only prone, sitting-opposite and sitting-under positions included unusable results, thus being the most challenging positions for heartbeat detection. This could be due to attenuation of the modulated radar signal caused by unfavorable signal reflections.

During both normal breathing and breath hold condition of the presence detection test, the variance of the occupied room radar signal was larger than the variance of the unoccupied room signal (Fig. 7). However, while the mean variance ratio of the breath-hold cases was 20, there were 9 measurements out of 60 where the ratio was under 2, which suggests that heartbeat does not

significantly contribute to the modulation of the radar signal, and the larger variance ratios were due to involuntary movements of the subjects.

The results of the one-subject general activity detection test indicate that the system also has potential for separating the activity types in a monitored room (Fig. 8). There is little difference between the empty-room conditions where the ventilation fans are on or off, but the different activities have clearly different variance ratios suggesting that the present system may be used for activity monitoring. More repeated tests with more test subjects are, however, needed to properly verify the reliability of the application.

Consistent with previous research [4], the aluminum-coated surfaces of the room seemed to strengthen the radar field. It is also possible that the reflective metal coating improved the radar signal coverage in the room, and thus enabled vital signs detection even in the challenging subject positions. Usually a metal sheet coating can be easily installed afterwards only to small-sized spaces. An economical option could thus be a metallic paint job on the room surfaces. However, the usability of the proposed system in a regularly-furnished room should also be evaluated.

5. Conclusion

In this study, an evaluation of a contactless Doppler radar-based system for detecting the vital signs and activity of a human subject in a radio-frequency shielded room was presented. The obtained results were promising. The presented method can be a potential option for reliable remote and contactless room-scale monitoring of vital signs, presence and activity.

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