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Feasibility Assessment of Doppler Radar Long-Term Physiological Measurements

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Abstract—**In this paper we examine the feasibility of applying doppler radar technique for a long-term health monitoring. Doppler radar was used to detect and eliminate periods of significant motion. This technique was verified using a human study on 17 subjects, and it was determined that for 15 out of 17 subjects there was no significant motion for over 85% of the measurement interval in supine positions. Majority of subjects exhibited significantly less motion in supine position, which is promising for sleep monitoring, and monitoring of hospitalized patients.**

I. Introduction

Development of reliable non-invasive physiological monitoring is an important goal in the modern healthcare research. Knowledge of routinely monitored cardiac and respiratory patterns would be clinically useful in many situations. Non-contact detection and monitoring of human cardiopulmonary activity is one of the most promising solutions for sleep monitoring, post-surgery monitoring, chronic healthcare, and home healthcare applications. Cardiopulmonary activity is the main parameter used in the study of sleeping disorders. Sleep apnea is a common condition, affecting more than 18 million Americans, according to the National Institutes of Health [1]. It is as common as adult diabetes and in many ways, as dangerous. Risk factors include gender, weight and age (being male, overweight, and over the age of forty), but sleep apnea can strike anyone at any age, even children. Sudden infant death syndrome is believed to be attributable to sleep apnea. The gold standard for the clinical diagnosis of obstructive sleep apnea syndrome (OSAS) is polysomonography (PSG), consisting of simultaneous recordings of electrophysiological and respiratory signals, during overnight monitoring of the patient in a specially-equipped sleep laboratory. Current techniques for measuring respiration effort/movement typically require direct contact with the patient through various chest bands that may impede unrestricted chest motion, or require the use of face masks which may change the subject's respiration and sleep pattern. In addition, the scarcity of sleep clinics and the expense associated with standard PSG allows treatments of small numbers of OSAS cases. The lack of awareness by the public and healthcare professionals, the vast majority remain undiagnosed and untreated, despite the fact that this serious disorder can have significant consequences. Untreated, sleep apnea can cause hypertension and other cardiovascular disease, memory problems, depression, and weight gain [2]. Moreover, untreated sleep apnea may be responsible for job impairment and motor vehicle crashes. A simple, less costly, noninvasive, reliable and ambulatory screening method for OSAS is desirable.

The development of Doppler radar for remote sensing of vital signs, with proof of concept demonstrated for various applications [3-6], could offer a platform to establish affordable, unobtrusive yet continuous healthcare monitoring system [7,8]. Without contact or subject preparation (special clothing, attachments, etc.), this could facilitate inexpensive sleep monitoring, enable continuous home monitoring for the chronically ill, allow fatigue monitoring to reduce work-related risk and automotive accidents, and deliver warnings of emergencies or changes in conditions of patients.

The Doppler radar detects all motion in the radar field of view, through detection of phase variations in the received signal. For a relatively still, seated or supine subject, this includes random fidgeting motion, and quasi-periodic positional variations of the chest surface due to cardiopulmonary activity. Despite significant advances in Doppler radar physiological monitoring, it is still a challenge to effectively isolate physiological motion from random fidgeting artifact interference. In this paper we examine the feasibility of applying Doppler radar technique for a long-term health monitoring.

Doppler radar is used to detect and eliminate periods of significant motion, and extract respiratory signals during the remaining interval. This technique was verified using a human study on 17 subjects, and it was determined that for 15 out of 17 subjects there was no significant motion for over 85% of the measurement interval in seated and supine positions. Majority of subjects exhibited significantly less motion in supine position, which is promising for sleep monitoring, and monitoring of hospitalized patients.

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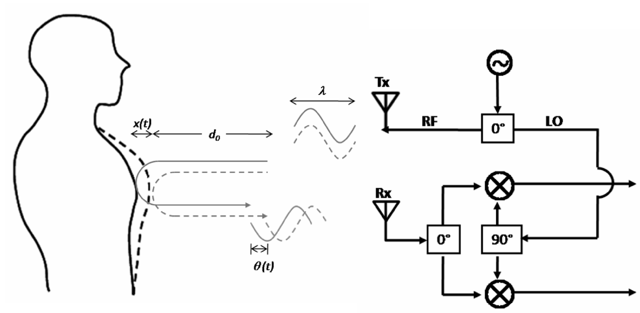


Fig. 1. A block diagram of a quadrature Doppler radar cardiopulmonary measurement system. The LO signal is divided by a two-way 90° power splitter to get two orthonormal baseband signals (I and Q) to ensure both channels are not in a minimum sensitivity spot.

II. Doppler Radar System

A short-range CW Doppler radar for physiological motion sensing, as shown in Fig. 1, transmits a radio wave signal and receives a phase-shifted signal reflected from a target, proportional to the surface displacement in the radar line of sight. A quadrature receiver is used to enable detection of the amplitude and direction of motion. In the complex plane, the position of the IQ constellation will be determined by the dc offset due to internal LO leakage, and clutter reflections. Periodic motion will map an arc in the complex plane, with magnitude of received RF power proportional to arc radius, and amplitude of motion proportional to the angle spanned by the arc. Subject fidgeting will result in irregular arc shapes, due to sudden changes in reference position and motion amplitude. These changes can be tracked and analyzed, to detect the periods of significant motion. Due to the resolution limitations of the current instrumentation, adjusted to detect minute chest displacement due to cardiopulmonary motion, typically it is not possible to effectively separate fidgeting motion and cardiopulmonary motion. Thus we propose to detect and eliminate the periods of significant motion, and extract cardiopulmonary parameters only during periods with no significant motion. In addition, the percentage of the interval with significant motion can be used as an aid in sleep studies, to for example determine the degree of restlessness, typically associated with sleep disorders.

The 2.4 GHz ac coupled system was used in this study for low cost and simplicity. Linear demodulation was chosen to recover the phase variations, since it is adequate for respiratory signal detection at 2.4 GHz, and is robust with respect to distortion due to ac coupling and noise. After demodulation, the threshold-based peak detection was used to identify the exact locations of respiration peaks, as well as detect the period of motion. Motion detection was based on sudden changes in amplitude of motion, and reference position. Duration of motion was measured, and statistical analysis performed on respiratory peaks detected when there was no significant motion.

III. Human Testing

The experiments were conducted according to the Committee on Human Studies (CHS) protocol number 14884. The protocol for this study was approved by the CHS of the University of Hawaii system. The data were taken from subjects in seated and supine positions. The subjects wore normal clothing and were instructed to breath normally during the measurements. The challenges in designing the test setup for this study were simultaneous measurement of reference and radar signals, human safety, and signal integrity. The reference respiration signals from piezoelectric sensors on a subject's upper and lower torso were captured through the Biopac data acquisition system (DAQ). The cardiopulmonary motion signals from Doppler radar were captured through the National Instrument DAQ. The two DAQ systems were synchronized with a marker signal from the Biopac system via an optical isolator and a National Instrument DAQ card (National Instruments NI-DAQ PCI-6009). The first pulse was sent out when Biopac DAQ started capturing data. The pulse train had different width to minimize the synchronization error.

The Doppler radar operated at 2.4 GHz with 0-dBm power level at the antenna connector. The radar system used these following commercially-available components: one transmitting antenna (Antenna Specialist ASPPT2988), one receiving antenna (Antenna Specialist ASPPT2988), two zero-degree power splitters (Mini-Circuits ZFC-2-2500), one ninety-degree power splitter (Narda 4033C), two mixers (Mini-Circuits ZFM-4212). The baseband output signals were amplified and filtered with low-noise amplifiers (Stanford Research Systems SR560) and then digitized with an onboard ADC of a National Instruments DAQ card (National Instruments NI-DAQ PCI-6259). The software to collect and process the data was written in MATLAB.

TABLE I
Summary of Biometric Info on the Study Population

Metrics	Mean±STD
Age	35.65±13.42 [yr]
Weight	70.37±12.27[kg]
Height	169.65±9.09[cm]
BMI	24.4±4.0
Max waist circumference	86.47±10.9[cm]
Min waist circumference	82.53±10.5[cm]
Max chest circumference	94.47±7.6[cm]
Min chest circumference	90.2±6.4[cm]
Max chest breath	30.93±4.4[cm]
Min chest breath	27.6±4.6[cm]
Max chest depth	23.57±3.0[cm]
Min chest depth	20.36±1.5[cm]

IV. Experimental Results

The results from seventeen healthy volunteers are presented in this study. Table I summarized the characteristics of all subjects participated. In both seated and supine positions, the antennas were one-meter away

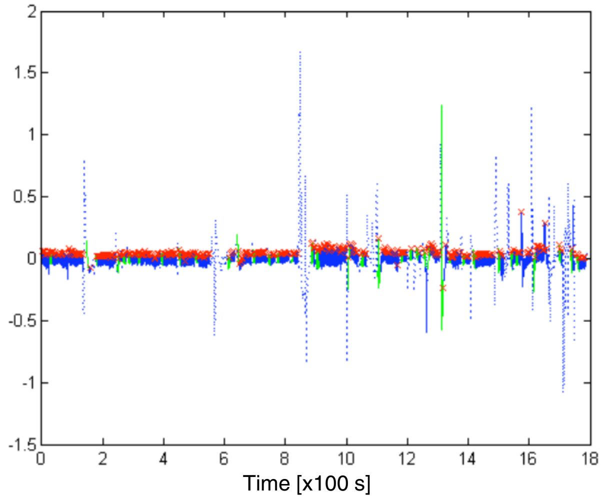


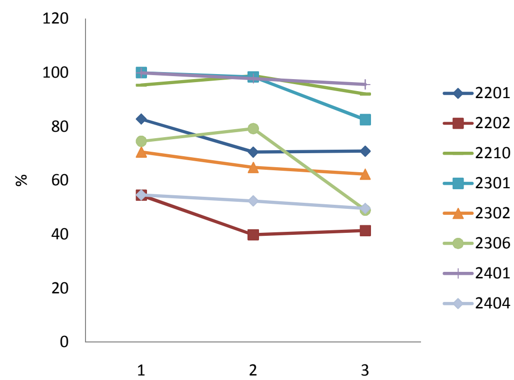
Fig. 2. An example of thirty minute data from the Doppler radar output after linear demodulation, taken for a seated subject. Red dots show the detected peaks, and dotted blue line shows detected periods of motion.

from the front torso of the subjects. The one-meter distance was chosen for mounting simplicity for supine measurements, however this distance can be easily extended for mounting the sensor on the ceiling. Data was taken for thirty minutes in the seated position, and ten minutes in supine position. Fig. 2 shows an example of thirty minute data from the Doppler radar output after linear demodulation, taken for a seated subject. Red dots show the detected peaks, and dotted blue line shows detected periods of motion.

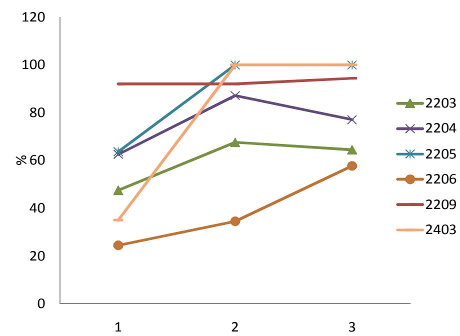
TABLE II
PERCENTAGE OF DATA WITHOUT MOTION ARTIFACTS

Subject	Seated				Supine
	30 minutes	1st ten	2nd ten	3rd ten	10 minutes
2201	75.32	82.79	70.54	70.86	35.57
2202	44.79	54.55	39.89	41.46	98.05
2203	59.70	47.53	67.63	64.46	46.32
2204	75.72	62.66	87.16	77.09	92.15
2205	88.09	63.66	100.00	100.00	97.81
2206	38.57	24.50	34.52	57.73	87.61
2209	93.00	92.06	92.06	94.44	97.38
2210	95.55	95.37	98.84	92.08	97.14
2301	93.55	100.00	98.41	82.55	100.00
2302	65.78	70.54	64.81	62.34	90.74
2303	65.61	64.74	61.34	70.43	91.99
2304	39.69	51.57	19.37	51.06	85.25
2306	67.40	74.51	79.21	48.97	100.00
2401	97.85	99.90	97.85	95.62	100.00
2402	99.19	100.00	97.52	100.00	99.40
2403	78.71	35.02	100.00	100.00	100.00
2404	51.75	54.62	52.40	49.64	98.46
Average	72.37	69.06	74.21	74.04	89.28

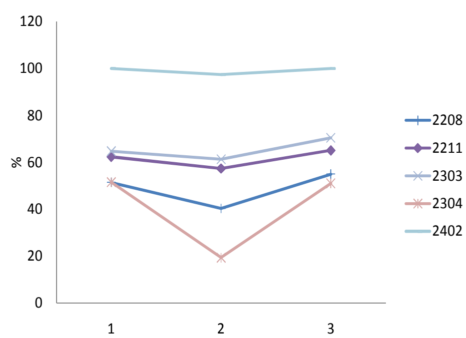
The duration of motion artifact period caused by subject movement could be considered as the activity period. The results showed the reality of how much data could be accurately extracted with the current system setup and algorithm. The 30-minute data were then divided into three segments of 10-minute data: the first ten minutes, the second ten minutes, and the last ten minutes, to evaluate which segment contain more activity periods in general. The results were mixed. Fig. 3 shows the percentage of radar signal without motion artifacts, which illustrates the behavior of human subjects. Almost equal portions of the subjects a) remained still at the beginning of the measurement then



(a)



(b)



(c)

Fig. 3. The behavior of human subjects varied from (a) remained still at the beginning of the measurement then started fidgeting, (b) started fidgeting at first then remained still in the rest of the measurement, and (c) remained still at first, started to fidget, and then back to still during the measurement.

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The results of seventeen subjects from 30-minute seated measurement (with their corresponding 10-minute segments) and 10-minute supine measurement are shown in Table II. The data from supine position contained less activity periods than seated position with only exception of subject 2201 and 2203.

Most subjects, as evident in Table II and Fig. 3, were not able to remain still for the entire duration of measurement, as shown. The behavior of subjects varied and can be categorized into three groups as mentioned. These three behavioral groups contained almost the same amount of subjects. On the average, each subject could remain still at approximately more than 72% of the data length for seated and 89% for supine positions. Moreover, in 15 out of 17 subjects there was no significant motion for over 85% of the measurement interval in supine positions. Doppler radar has been proven to be a possible tool for remote sensing of vital signs. The experimental results in this study shows that Doppler radar could be used as a means of determining how much the person moves, which is useful for sleep studies.

V. Conclusion

The results presented in this paper have shown that Doppler radar can be used as a tool for detecting periods of significant motion during physiological monitoring. While this remote physiological sensing technique is currently limited to sedentary and supine patients, due to difficulty with extracting cardiopulmonary signals in the presence of gross subject motion, the capability to extract respiration and heart signals independently provides a powerful tool for future health monitoring. This technique may be particularly suitable for sleep apnea monitoring, infant SIDS monitoring, fatigue monitoring, in-hospital monitoring, and home health care.

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