Research Progress in Millimeter Wave Radar-Based non-contact Sleep Monitoring - A Review

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***Abstract*- Compared with traditional contact medical devices, non-contact sleep monitoring based on millimeter wave radar has the advantages of non-contact, simple operation, and long-term monitoring of human respiration rate (RR) and heart rate (HR), which has broad research value and market prospects. In this paper, we review the recent developments, current challenges and future directions in the field of non-contact sleep monitoring based on millimeter wave radar. We first summarize some representative research works published in recent years to discuss vital sign monitoring, sleep posture estimation, and obstructive sleep apnea (OSA) detection. It is illustrated that vital signs such as RR and HR can be used as indicators for diagnosing many diseases, helping to diagnose sleep disorders and providing information on the classification of different sleep stages. Sleep posture estimation can be used as a diagnostic indicator for many chronic diseases and may help in pharmacological treatment. OSA monitoring is one of the most valuable research and application prospects in sleep monitoring. Finally, the challenges now facing measurement accuracy and stability, multi-user monitoring, and processing device computational performance are discussed, and future research directions in the field of sleep monitoring are proposed.**

Index Terms: **millimeter wave radar; sleep monitoring; vital sign monitoring; sleep posture estimation; OSA detection.**

I. INTRODUCTION

Due to the increasing pace of people's lives, the pressure from the internal and external environment is increasing, which leads to various sleep-related diseases. The main common diseases related to sleep are insomnia and obstructive sleep apnea (OSA), among which the very harmful one is OSA, which has been shown to be associated with ischemic heart disease, coronary artery disease, atrial fibrillation (AF), chronic heart failure (CHF) and sudden cardiac death [1] which pose a threat to the health of patients but are not easily detection and treatment, and sleep monitoring can prevent and detect these related diseases in advance, so one of the most promising applications in healthcare is sleep monitoring.

Traditionally, the gold standard for sleep monitoring is the polysomnography (PSG) system, but this method usually has disadvantages such as expensive equipment, complex operation, high physician requirements and low diagnostic efficiency, and is not suitable for long-term continued monitoring use [2], making a great demand for non-contact sleep monitoring systems. Radar can be effectively used to characterize several biomedical parameters without contact and to detect emergency situations such as apnea, heart rate irregularities, sudden infant death syndrome and falls [3], which can also provide excellent long-term care benefits. Therefore, millimeter wave radar-based sleep monitoring has the advantages of non-contact, simple operation, and the ability to monitor human respiration and heart rate for a long time, which can be done without disturbing people, and has a broad research value and market prospect, however, it is still too early to be studied for universal home application.

In [4], Walid et al. reviewed the recent advances in the field of radar-based sleep monitoring and current industrial progress, while this paper aims to review the recent developments and current challenges in the field of millimeter-wave radar-based non-contact sleep monitoring. In the next sections, we first explore the recent academic research in the field of millimeter-wave radar-based non-contact sleep monitoring, then discuss the current challenges and future directions of sleep monitoring research, and finally conclude the paper.

II. ADVANCES IN SLEEP MONITORING

Research on millimeter wave radar-based sleep monitoring focuses on the following aspects: vital sign monitoring, sleep stage classification, sleep posture estimation, and sleep disorder inference, while OSA detection is of great interest in sleep disorder inference research. Among them, vital sign monitoring and sleep posture estimation are the basis for sleep stage classification and sleep disorder inference, and only the accurate and stable results of the former can make it possible to obtain accurate results of the latter. Due to space limitation, we focus on three aspects of vital sign monitoring, sleep posture estimation and OSA detection, and use a classification of three themes to present some representative research works published in recent years. Table I summarizes the radar processing algorithms or classification algorithms used in these studies and the final results obtained.

TABLE I
ADVANCES IN SLEEP MONITORING

	YEAR	ALGORITHMS	RESULTS	WORK
Vital Signs Monitoring	2019	TARGET TRACKING ALGORITHM	2.6M,RR:96.76%, HR:88.88% 5.4M,RR:96.76%, HR:88.88%	[5]
	2017	Two-parameter LMS filter	More accurate than BPF and WT extraction methods	[6]
Sleep Posture Estimation	2021	Monitoring the displacement amplitude of the ERCS	POSE ESTIMATION ACCURACY IS 100%	[9]
	2019	MACHINE LEARNING	POSE ESTIMATION ACCURACY IS 88.5%	[10]
OSA Testing	2019	Monitoring the displacement amplitude of the ERCS	OSA event accuracy of 92%	[11]
	2020	MACHINE LEARNING	OSA event accuracy of 96.7%	[12]

A. *Vital Signs Monitoring*

Vital signs such as respiratory rate (RR) and heart rate (HR) are very important in vital sign monitoring. These signs can reflect information about an individual's overall health status and can be used as indicators to diagnose many diseases, help diagnose sleep disorders and provide information on the classification of different sleep stages. Abnormal HR and RR are likely to be indicative of some kind of health problem, such as heart problems, obstructive sleep apnea, etc. People enter different stages of sleep with different physiological states, and the RR and HR will be different in each stage, so vital signs monitoring can provide information on the different sleep stages.

In [5], Mercuri et al. proposed a target tracking algorithm, random body motion suppression radar algorithm, which can operate in the presence of strong clutter reflectors and moderate limb movements included. According to the obtained experimental results, the extracted RR and HR at 2.6 m when the subject was in the range of 3 bpm. had a window percentage of 96.76% and 88.88%, respectively. When subjects were at 5.4 m, the percentages were 94.13% and 89.76%, respectively. In this paper, He et al. used FMCW wideband radar capable of monitoring and target localization of multiple important signals at low signal-to-noise ratios[6]. His proposed two-parameter LMS filter-based method for respiration and heartbeat signal extraction is more accurate compared to band-pass filter (BPF) method and wavelet transform (WT) method.

B. *Sleep Posture Estimation*

Several clinical studies have shown that the identification of the major categories of posture during sleep can be used as a diagnostic indicator for a variety of chronic diseases and may help in pharmacological treatment. For example, avoiding the supine position can reduce the severity of sleep apnea syndrome [7] and reduce the risk of sudden infant death syndrome (SIDS) [8]. Therefore, identifying the categories of sleep positions is of great value.

In [9], Kiriazi et al. used dual-frequency Doppler radar to estimate sleep posture. The amplitude of the displacement of the effective radar cross-section (ERCS) was monitored to distinguish whether the subject was in a supine, prone or lateral sleep position. The dual-frequency radar algorithm complemented the accuracy limitations of 2.4 GHz radar and 5.8 GHz radar and was able to correctly estimate and classify the posture of all subjects. Higashi et al. used Doppler radar time-domain signal processing using a machine learning approach for sleep posture estimation [10]. According to the results they obtained, the accuracy of the posture estimation was 88.5% in six subjects.

C. *Obstructive Sleep Apnea Testing*

One of the most valuable research and application prospects in sleep monitoring is OSA monitoring.

Baboli et al. used dual-frequency Doppler radar to detect OSA [11]. Orthogonal microwave Doppler radars of 2.4 GHz and 24 GHz, respectively, were used, resulting in a phase difference of 90 degrees, where the 2.45 GHz radar distinguished between normal and paradoxical breathing and the 24 GHz radar separated apnea and hypopnea, combining the two to improve the comprehensive performance of respiratory monitoring. An overall sensitivity of 86% for apnea-hypoventilation events, a specificity of 91% and accuracy of 92%. In [12], Snigdha et al. used a combination of microwave Doppler radar and a machine learning classifier to detect OSA. a clinical study of different participants using a microwave Doppler radar system was conducted to explore the feasibility of the ERCS method to identify different OSA events, where OSA events were classified as normal breathing, apnea, and hypopnea. The experimental results showed that the classification accuracy of the quadratic kernel SVM classifier for OSA events was 96.7%.

III. PRESENT CHALLENGES AND FUTURE DIRECTIONS

The transition of millimeter wave radar-based non-contact sleep monitoring technology from the laboratory to widespread home application still needs to overcome many difficulties, and the following are the challenges faced now and the future directions.

A. Measurement Accuracy and Stability

Most current radar systems for biomedical applications are aimed only at vital sign monitoring under ideal conditions, i.e., on a relatively stationary person (e.g., sitting or lying down). However, in practical scenarios, it is far more complicated than the ideal situation, such as unpredictable body movement-related noise, changes in body orientation, sleep posture, test environment, and other factors that make the radar signal very susceptible to interference by the clutter generated by these random movements. The accuracy and stability of the measurements obtained by traditional methods face big challenges, and new or improved signal processing methods are needed in the future to get better radar detection capabilities, such as machine learning, deep learning [13] and other methods.

B. Multiuser Monitoring

Multi-user monitoring is also a big challenge nowadays. Most of the current studies are on single person sleep monitoring and the conclusions drawn are also about the accuracy of identifying sleep health conditions (e.g., HR, RR, OSA) in a single person. However, in everyday households, multiple people, people and pets [14] in bed like this is a common scenario, so it is not enough for general application in households now. In the future, it should be necessary to accurately assess the identity, characteristics, sleep conditions, and health assessment of different objects, and give each family member an archive in which the sleep health information of these members is stored, so that users can clearly understand the sleep health status of family members. Therefore, multi-user monitoring is significant and also an important direction for future research, which requires more research progress in academia.

C. Processing Equipment Computing Performance

As the research on millimeter wave radar-based sleep monitoring continues to deepen, new signal processing algorithms such as machine learning and deep learning have been greatly applied in the field of sleep monitoring, and the experimental scenarios have gradually changed from single, stationary, to multiple, sleep posture switching such complex scenarios, making the radar detection capability in the field of millimeter wave radar-based sleep monitoring has made great progress. With the increase of algorithm complexity and diversification of application scenarios, but for the radar equipment, the need for real-time processing of radar data and signal processing algorithms and get accurate results, which requires a very powerful computing power of the radar equipment processor, so the processing equipment computing performance also faces a great challenge.

IV. CONCLUSION

This paper reviews the recent developments and current challenges and future directions in the field of non-contact sleep monitoring based on millimeter wave radar. We first summarize some representative research works published in recent years to discuss vital sign monitoring, sleep posture estimation, and OSA detection. It is illustrated that vital signs such as RR and HR can be used as indicators for diagnosing many diseases, helping to diagnose sleep disorders and providing information on the classification of different sleep stages. Sleep posture estimation can be used as a diagnostic indicator for many chronic diseases and may help in pharmacological treatment. OSA monitoring is one of the most valuable research and application prospects in sleep monitoring. Finally, the challenges now facing measurement accuracy and stability, multi-user monitoring, and processing device computational performance are discussed, and future research directions in the field of sleep monitoring are proposed.

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