Sleep-Monitoring Technology Progress and Its Application in Space

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INTRODUCTION: Sleep is an indispensable physiological phenomenon. The complexity of sleep and the time it occupies in human life determine that its quality is positively correlated with human health. Since polysomnography was used in spaceflight in 1967, the sleep problem during astronaut flight has been studied in depth for more than 50 yr, and many solutions have been proposed, but astronauts have always had sleep problems during orbital flight. Insufficient sleep and changes in the rhythm of human sleep-wake activity will lead to disturbance of the human body's internal rhythm indicators, which will lead to psychological and emotional fluctuations and reduced cognitive ability, decision-making ability, teamwork, and work performance. NASA has identified operational errors due to sleep deprivation and altered circadian rhythms as an important risk factor in the key biomedical roadmap for long-term flight, so the importance of sleep monitoring in spaceflight is self-evident. On-orbit sleep-monitoring methods include both subjective and objective aspects. We review objective sleep-monitoring technology based on its application, main monitoring physiological indicators, intrusive advantages, and limitations. This paper reviews the subjective and objective sleep evaluation methods for on-orbit applications, summarizes the progress, advantages, and disadvantages of current ground sleep-monitoring technologies and equipment, and looks forward to the application prospects of new sleep-monitoring technologies in spaceflight.

KEYWORDS: sleep-monitoring equipment, sleep-monitoring technology, spaceflight sleep problems.

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Environmental factors such as weightlessness in space, radiation, airtight isolation, weak magnetic fields, and circadian rhythm disturbances have extensive effects on human physiology and psychology.[31,48] Lack of sleep and poor sleep quality are common problems for astronauts in spaceflight.[51] As early as during the Apollo mission, although sleep monitoring was not carried out, it was found through astronaut interview records that almost all astronauts had problems such as sleep fatigue before flight.[1] Sleep is affected by the low temperature in the spacecraft, loud noise, and the cramped sleeping bag, and some astronauts even say that the continuous sleep time does not exceed 3 h.[43] In the Skylab mission, the M133 sleep monitoring test was carried out, and Frost reported for the first time that the average sleep time of the three Skylab astronauts on orbit was only $6\,h \cdot d^{-1}$, which was nearly 1 h less than the average time on the ground.[22] During the U.S. space shuttle mission, STS-90 and STS-95 (launched in 1998) carried out a comprehensive sleep study.[6] Dijk et al. observed five astronauts (four men and one woman) and found that the on-orbit sleep time was $6.5\,h \cdot d^{-1}$, as well as the following: sleep quality decreased, the amplitude of body temperature rhythm decreased, the circadian rhythm of urinary cortisol disorder occurred, and slow-wave sleep time decreased.[19] Since then, NASA has continued to carry out sleep research. In 2014, Barger et al. collected sleep-monitoring data from 64 astronauts on 80 STS missions and 21 astronauts on 13 International Space Station (ISS) missions, then compared them with all astronauts' ground data. It is pointed out that the average sleep time of astronauts is

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about 6 h · d^{-1} during spaceflight, and sleep deprivation not only occurs during STS and ISS missions, but also during the training period of 3 mo before flight.[5]

Ground-based experiments show that lack of sleep affects work performance. Sleeping less than 6 h for two consecutive nights was associated with worse work performance, and 4 or 6 h of sleep per day for 14 consecutive days was equivalent to 48 or 24 h of sleep deprivation. The study found that 72 h of closed isolation in a closed-isolation environment will slow down the perception speed, the effect will be greater when combined with sleep deprivation, the response will be prolonged, and the accuracy rate will decrease in the middle and late stages. MRI results showed that sleep deprivation impairs the function of the brain's attentional network and the control of the cerebral cortex over the lower center is weakened. Under the Martian time conditions of a non-24-h light–dark cycle (24.67 h), although the human sleep–wake activity rhythm can be synchronized with the environmental time, the internal rhythm indicators of the human body are disordered: urine electrolyte rhythm disorder, body-temperature-heart-rate phase out-of-sync with the ambient light, etc., and individuals have psychological mood swings and negative emotions due to rhythm disturbances, leading to reduced team performance. NASA has identified operational errors due to sleep deprivation and altered circadian rhythms as important risk factors in the key biomedical roadmap for long-term flight.[12]

In view of the above situation, the application of sleep-monitoring technology in aerospace has become particularly important. However, due to the weightlessness of spaceflight and the limited load of spacecraft and space stations, the on-orbit application of sleep-monitoring equipment is limited. In 1967, the U.S. Gemini 7 mission used EEG to record and analyze astronauts' on-orbit sleep. However, due to technical problems such as electrode fixation, the recording time was less than 55 h, only two sleep cycles were recorded, and sleep characteristics were not effectively analyzed.[47] In subsequent sleep studies, in addition to subjective sleep-evaluation methods such as sleep logs, on-orbit medication records, and sleep questionnaires, rhythm-related biochemical indicators were detected and sleep-monitoring equipment was also used, such as polysomnography and Actiwatch, which became the main way of on-orbit sleep-monitoring after 2001. The equipment used for on-orbit sleep monitoring has undergone many years of development, from the earliest polysomnography to the Actiwatch that NASA has been using on-orbit—especially the Actiwatch, which is accurate in judging an individual's "wake–sleep" state. It has been recognized that it can complete the on-orbit monitoring task to a limited extent, but it is obviously limited in terms of sleep latency and sleep stage assessment. The sleep assessment methods currently used on-orbit, whether subjective or objective, have their own shortcomings. Starting from the sleep problem in spaceflight, this paper summarizes the current on-orbit sleep-monitoring technology (equipment), and discusses the feasibility of applying new sleep-monitoring technology (equipment) in spaceflight in order to better prevent and solve the problem of astronauts' sleep on orbit.

Sleep assessment must take into account factors such as the diagnostic process, subject acceptance, cost, and the importance of understanding sleep in a natural sleep environment and documenting sleep structural characteristics. Sleep-monitoring methods include both subjective and objective aspects.

Subjective assessments mainly include interviews, sleep scales, sleep diaries, etc. Detailed clinical interviews are first-hand information for diagnosing sleep disturbances, and additional evaluations are sometimes required, especially if interviews are not available, as may be the case with in-orbit astronauts. Sleep scales are also one of the important methods of sleep assessment. There are about 70 kinds of insomnia-related scales.[38] The advantages of sleep scales are that they are simple to operate and put almost no pressure on the respondents; but the defects are also obvious: 1) recall bias may occur; and 2) may have great interference by the respondents. Sleep logs are often used in the behavioral treatment of sleep disorders such as insomnia, and their advantage is in providing a data basis for daily sleep changes, but their limitation is that the pressure of the recorder is higher compared with that of the sleep questionnaire since they require recording the sleep situation every day; at the same time, sleep logs are greatly affected by the recorders' expectation of the sleep situation. For example, when using a sleep diary to keep a sleep schedule, there have been reports of bedtimes being a full hour earlier than what was reflected in the activity monitor.

Objective assessment refers to various sleep-related physiological, biochemical, behavioral, and other objective indicators collected by instruments or sensors, such as EEG, electromyography (EMG), eye movement, limb activity, cortisol, melatonin, etc., with relatively high reliability.[3,11] The current evaluation standard is polysomnography and physical activity-monitoring is also a commonly used objective evaluation equipment.[16] The information collected by instruments or sensors has its own advantages, such as being less affected by the subjective factors of the subjects themselves, while the body activity monitor has a lower cost than the "gold standard" polysomnography monitor and has little interference with the sleep of astronauts. Therefore, it is used in more and more spaceflight missions, such as Actiwatch.

Sleep monitoring in spaceflight mostly uses objective instruments combined with subjective assessment. Subjective sleep-monitoring methods used in aerospace sleep monitoring include flight logs, sleep logs, astronaut diaries, astronaut interviews/questionnaires, and medication records. Among them, the sleep log can directly reflect the sleep status of astronauts on orbit, before takeoff, and after landing, and others can be used as auxiliary verification methods.[51]

In 2018, Chen and others found through a questionnaire that sleep quality was better after a flight than before or during a flight.[13] In 2014, Barger et al. found in a study based on astronaut flight logs that most astronauts' sleep time on the space station decreased during flight, relative to both preflight and postflight.[5] However, in 2013, Basner et al. studied the sleep logs of astronauts and showed that astronauts subjectively believed that their sleep quality was okay.[7] In the same year, Whitmire and others studied the questionnaire survey and astronaut interviews after the astronauts returned and showed that 52% of the astronauts thought that they slept better during the flight, while 6% of them thought that their sleep became worse.[50] In 2010, a study by Stuster et al. based on the diaries of astronauts on the ISS showed that astronauts' sleep quality deteriorated during flight.[47] Earlier studies used methods similar to those described above.

The objective sleep-monitoring methods used in aerospace sleep monitoring mainly include polysomnography and body movement monitors. Other methods that can be used as auxiliary verification methods include the use of sleep aids and the monitoring of some biochemical indicators (related to biological rhythms) such as body temperature, melatonin and salivary cortisol levels, etc.

The world's first on-orbit EEG recording was performed during the Gemini 7 mission. Due to technical issues, only the first few hours of sleep were recorded and analyzed. Two sleep cycles were observed. Both the quantity and quality of sleep on the first night were insufficient. On the second night, Borman went through four sleep cycles that were considered normal: each cycle was about 90 min, but there were multiple arousal states along the way.

After the Gemini 7 mission, polysomnography was performed several times for sleep recording. In the STS-90 and STS-95 missions, polysomnography was used to record and analyze the six astronauts' sleep. The polysomnography they used has been modified for on-orbit recording tasks, called "PI-in-the-box", including three modules of EEG, electrocardiography (ECG), and EMG. There are also some short-duration missions using this type of sleep recorder. In the STS-78 mission, the astronauts also used a similar device called the medilog sleep research recording system, which also includes the three modules above. Since then, the three modules of EEG, ECG, and EMG have basically become the most used equipment for on-orbit sleep research.

Most recently, in 2019, Petit et al. reported 6-mo EEG monitoring of five astronauts on the ISS, including a 70-min awakening period and then 2 h and 10 h after waking up.[39] In 2005, Stoilova et al. studied 27 polysomnography data of Mir space station astronauts.[45] In 2001, Dijk et al. used polysomnography and body-motion-monitoring to study five astronauts on two missions (16 d and 10 d).[19] In 2000, Stoilova and others studied the use of polysomnography to monitor the situation of five astronauts on the Mir space station.[46] In 1999, Stickgold and others used polysomnography to monitor 5 astronauts and recorded a total of 317 nights of sleep data, which also included 3 dimensions of data before the flight, during the flight, and after landing.[44] In 1998, Monk et al. monitored four astronauts simultaneously using polysomnography and motion monitors during a 17-d mission.[34]

The body activity monitor that has appeared most frequently in space missions is the Actiwatch, which has been used as a sleep-monitoring device in the ISS and recent American space missions. With more than 20 yr of clinical and market verification since the American Sleep Disorders Association guidelines were created in 1995, Actiwatch has attracted more and more attention as the most outstanding sleep-monitoring application product with an accelerometer sensor.[35,41,42]

Most recently, in 2020, Chen et al. conducted a 15-d short-term flight test of three astronauts using body-motion-monitoring technology for 63–54 d before flight, 3–14 d in flight, and 0–14 d after flight of continuous monitoring[13]; in 2016, Flynn-Evans et al. monitored 21 ISS astronauts for up to 6 mo, with a total of more than 3248 d of data, and the data they released also included the 11 d before flight.[20] In 2014, Barger et al. summarized 80 spaceflight missions by 64 astronauts and 13 ISS missions by 21 astronauts, with more than 8000 d of data, including preflight, in-flight, and postflight body-motion data.[4] In the above research, the body-motion detection equipment has been rapidly applied in spaceflight due to its advantages of simplicity and occupying little space, and its accuracy has been gradually improved in previous flight experiments. As it can only judge the sleep states and cannot tell the detailed sleep cycle of astronauts, there is still room for improvement in spaceflight sleep monitoring.

Advances in Objective Sleep-Monitoring Technology

Objective indicators such as EEG, heart rate, and body movement will undergo various changes, and these changes are related to the sleep period. Internationally, it is mainly distinguished by different EEG states, meaning the general sleep-staging standard currently proposed by Rechtschaffen and Kales. Based on the American Academy of Sleep Medicine,[9,26] sleep is divided into two periods: nonrapid eye movement sleep and rapid eye movement sleep. Poor sleep quality mainly has such characteristics: 1) disturbed sleep structure; 2) too short (somnia) or too long (insomnia); 3) difficulty maintaining sleep; and 4) excessive arousal events. During the whole night of sleep, different sleep depths will be accompanied by different EEG changes. The longer the N3 and rapid eye movement periods in the whole night's sleep and the shorter the awakening period, the better the quality of the night's sleep. During sleep, the body movement, heart rate, and respiration rate also show rhythmic changes similar to EEG with the changes in sleep stages.[54] According to this change, Yu et al. realized the recognition of wakefulness sleep, and the recognition rate has reached more than 90%, whereas the recognition rate of other sleep stages is about 75%.[55] Heart rate variability is also closely related to the conversion and recognition of sleep states. However, there is not enough study about heart rate variability during sleep in spaceflight.

Nowadays, most of the objective sleep-monitoring evaluation methods are various sleep-monitoring equipment, such as polysomnography. However, as in the shortcomings mentioned above, in the research direction of sleep-monitoring equipment, most researchers focus on extracting features from physiological signals such as heart rate, body movement, respiration, illumination, etc., and compare them with the gold standard polysomnography to find a monitoring method that is less disturbing and is more convenient to use.

Infrared biosensors monitor the user's sleep through infrared and can also track the user's heart rate and breathing.[57] An et al. reported that infrared optical gas imaging can directly measure the respiratory airflow, allowing more accurate identification of the breathing and sleep conditions.[2] The principle of infrared monitoring is to use a special electronic device to convert the temperature distribution on the surface of the object into an image and monitor the temperature distribution.[32]

The accelerometer is mostly used in wearable products, and the detection technology they use is not the same. The most used is the gravitational acceleration sensor.[29] This sensor will generate signals when the body undergoes inertial motion, even if it is a tiny movement. These wearable devices have many different manifestations, such as wristbands, armbands, smartwatches, headbands, rings, sensor clips, etc.[18] Wearable devices that monitor sleep based on body movements have been on the market since the 1970s. They have a built-in accelerometer, which can calculate awake and sleep time as well as other parameters from physical activity. The body movement instrument is easy to wear, avoids cumbersome constraints such as wires, and can be used continuously for many days, but it cannot perform sleep staging and its accuracy has yet to be verified. In fact, according to a large number of comparative studies with polysomnography, it can barely detect drowsiness, underestimates the latency to fall asleep, and overestimates the number of microarousals. Therefore, activity measurements are limited to subjects with circadian rhythm disturbances and the assessment of total sleep time.[36] It can only be an auxiliary method for sleep assessment.

The piezoelectric sensor, which is a kind of sensor based on the piezoelectric effect, here mainly refers to the sensor technology applied in contact devices (such as mattresses) through pressure measurement and also includes electrical coupling technology as well as resistive and capacitive sensors. At present, there are many sleep-monitoring products on the market based on the piezoelectric sensor. Most of them can be placed under or near the mattress. One example is the Beddit made by Apple Inc. The main use is to analyze the data and judge sleep quality according to different algorithms. The analyzed indicators usually include heart rate, respiration, sleep time, and body movement.

In addition, Yu et al. used partitioned mattress-monitoring to sense the micromotion of various parts of the body and wavelet analysis technology to accurately obtain beat-by-beat cardiac cycle information. The signal-processing method of the mattress comes from the wavelet transform method. In the test of 24 normal people, the average coincidence rate between the classification of natural sleep mechanisms and artificial EEG sleep staging has reached 85%.[53]

Cao and others studied the ballistocardiogram integral signal obtained from the thoracic shock map, detected its characteristic points, calculated characteristic parameters, and identified the body motion complex, then designed a set of noninvasive respiratory detection parameters based on the shape and amplitude characteristics of the body motion complex.[10] Jiao et al. designed a mattress-type sleep-monitoring system based on flexible force-sensitive sensors.[28] The verification results show that the deep sleep stage has a high correlation with body-movement fluctuations.

The device based on photoplethysmography technology takes an MSP430 microcontroller as the core and is composed of a pulse oximeter probe (usually wrap-around), light source, Bluetooth communication circuit, etc.[52] When the device is working, the light signal from the end of the human finger is collected by the blood oxygen probe. The probe outputs a relatively weak current signal, which is processed by the signal conditioning circuit and sent to the host computer for processing by means of Bluetooth communication. The measurement principle of photoplethysmography technology is based on Lambert Beer's law: when two different wavelengths of light pass through the end of the finger, affected by the change of blood volume, the light absorption will change, and a photoplethysmographic wave will be generated. Using the photoplethysmography technique, Ji studied the extraction of two nonstationary time series of ECG signal R-wave peak point and pulse wave trough values, carried out preliminary processing of autocorrelation and cross-correlation, and used the algorithm to calculate. The five feature parameters are input into the support vector machine for classification, and the classification test results of sleep staging have an accuracy of 79.45%.[27,56] The sleep apnea syndrome detection device based on the wrap-around blood oxygen probe, by Wu and others, was measured in the experimental test period with 10 volunteers, and the error is within ± 1% compared with the standard product. Deviaene et al. studied an automatic screening method for sleep apnea based on the detection of apnea and hypopnea events in the blood oxygen saturation signal and also confirmed that it is more effective.[17]

Bioradar products are also one category of sleep-monitoring products. The predecessor of bioradar technology is military high-frequency, low-power radar technology. Ultra-broadband does not produce ionizing radiation, produces high-resolution fluctuations, penetrates solid objects and human tissue, produces ultra-low power-specific return waves, and is received by established narrowband systems. As early as 2008, the American company Sensiotec launched the world's first truly noncontact vital signs detection system, using ultra-wideband technology, and won the International Technology Innovation Award that year. However, the company withdrew from the market in 2016 due to technical and commercial reasons.

The product with the earliest start and the most comprehensive product technology in the civil field of bioradar in China is the Zhuhai Ogilvy Health Technology Co. Ltd. This product has successfully realized the miniaturization of hardware equipment and can be installed on the walls and ceilings of the subjects' houses. This method is concise and has no side-effects. Especially by using the neural network deep learning algorithm, the accuracy of heart-rate calculation has been greatly improved, which can reach more than 95%. Unfortunately, the data used in these reports have not been made public, and its accuracy cannot be verified. **Table I** is a comparison of the above sleep-monitoring technologies.

The gold standard for the diagnosis of sleep apnea syndrome is polysomnography. There are nine parameters such as blood oxygen and body position, which are also the physiological parameters monitored by most sleep-monitoring instruments. Sleep structure is reflected by monitoring EEG, electrooculogram, and EMG. Interpretation of respiratory events is accomplished by the following: monitoring oral and nasal airflow, chest and abdominal breathing movements, snoring, body position, etc.; monitoring blood oxygen saturation to reflect whether the body is hypoxic and the degree of hypoxia; and monitoring ECG to reflect the state of cardiac function. Monitoring is mainly composed of three parts: 1) analysis of sleep structure, processing and monitoring of abnormal EEG; 2) monitoring sleep-breathing function to find sleep-breathing disorders and analyzing their type and severity; and 3) monitoring sleep cardiovascular function. However, the disadvantages of inconvenient operation and uncomfortable wearing are obvious. The device itself has a negative impact on sleep quality. Data collection needs to be carried out in the laboratory, which changes the usual state and introduces new variables in the diagnosis process. It is not used in many practical applications and is not recommended as the primary means of sleep assessment.

In response to such shortcomings, portable sleep detectors have gradually developed. Generally, they only monitor parameters such as breathing, chest and abdominal movement, ECG, and blood oxygen. There are also portable devices that can be extended to monitor EEG. Portable sleep monitoring is mainly used for the assessment and diagnosis of obstructive sleep apnea syndrome. Compared with polysomnography, it has fewer monitoring parameters, lower cost, easier operation, and can be monitored at home, but the disadvantage is that it has fewer electrodes and can only monitor part of the EEG to meet basic monitoring needs.

Another integrated device is in the form of pajamas. Multiple sensors, which include capacitive sensors, inductive sensors, piezoelectric sensors, optical sensors, chemical-biochemical sensors, and piezoresistive sensors, are embedded in the pajamas to monitor the movement of the human body, heartbeat, body temperature, and respiration. Obviously, clothing like pajamas provide a platform to deploy sensors in the near space and act as an interface between the wearer and an electronic/information system by converting human physiological/environmental or other signals into measurable electrical signals.[21,33] This kind of device has low sleep-staging accuracy; the breathing signal is muscle vibration rather than nasal airflow, so the recognition rate of apnea is low.[25,49]

In recent years, applications that make full use of smartphones as user-monitoring devices have also begun to develop slowly. The powerful computing power and sensor-tracking tools of smartphones are used for sleep monitoring and sleep quality assessment. The available sensors include acceleration sensors, microphone sensors, and light sensors, and some are also combined with GPS positioning systems. There are hundreds of applications based on iOS or Android systems that record the health data of users through smartphones.[30] Behar et al. studied sleep-monitoring applications for smartphones, some of which use accelerometer and microphone sensors to capture data for sleep quality assessment by simply placing the

Table I. Comparison of Sleep Monitoring Technologies.

TECHNOLOGY	APPLICATION	MAIN MONITORING PHYSIOLOGICAL INDICATORS	INTRUSIVE	ADVANTAGES	LIMITATIONS
Infrared Biosensor Technology	Infrared imager	Heart rate, breathing	Low	No sleep disturbance	The sleep staging accuracy is average, and the anti-interference ability is poor
Accelerometer Technology	Wristwatch	Body movement	Low	Simple and easy to use, basically has no disturbance on sleep	The accuracy of sleep staging is poor
Photoplethysmography Technology	Blood oxygen probe sleep monitoring device	Blood oxygen, pulse wave	Relatively low	Low sleep disturbance	Average sleep staging accuracy
Piezoelectric Sensor Technology	Sleep Mattress	Heart rate, breathing, physical activity	Relatively low	Low sleep disturbance	Accuracy of sleep staging is average, the signal is generally saturated during body movement, and cardiac shock and respiratory waveforms cannot be obtained under body movement.
Bioradar Technology	Bioradar	Breathing, movement, heart rate	Low	No sleep disturbance; rough sleep staging analysis	Sleep staging accuracy cannot be determined

phone on the bed or close to the body, such as Sleep Cycle and Sleepbot, etc.,[8] but the accuracy of this method remains low. Gu et al. used a similar approach to assess the sleep quality of users at different sleep stages by measuring the duration of the phone in a fixed position rather than recording certain sleep-related activities.[23] But all of these apps require the cooperation of the user to monitor the location of the phone. The phone may drop or be unable to measure data due to a bad location or other environmental reasons, such as occlusion. Meanwhile, there are also concerns about whether battery usage can cause other health problems that make it unsuitable for long-term sleep tracking.[14] ISleep can assess the user's sleep quality by analyzing sound events, so there is no need to put the phone on the bed. The requirement of relative body position does not need to be particularly close.[24] However, there is little evidence to calculate the accuracy of sleep quality assessment with devices such as smartphones, and the results may only be used as a reference for scientific research now. Several common sleep monitoring integrated devices are compared in **Table II**.

Application Prospects of Sleep Monitoring in Aerospace

In the current situation, subjective sleep-monitoring methods are widely used in aerospace; most of the subjective monitoring methods are greatly affected by individual differences, but completely opposite results have also occurred in aerospace applications.[4] It is also found that subjective perception may deviate from reality compared with objective data. Therefore, recent aerospace sleep research focuses more on objective monitoring methods, supplemented by subjective methods.

Equipment used for in-flight applications must meet certain standards. One of the main requirements is to minimize resource consumption in terms of the physical conditions of the device, such as mass, power and volume, storage conditions and power consumption. Unlike on Earth, these devices need to be modified to meet space certification requirements. The equipment for space should be very compact and fully integrated.[40] Strategies to achieve this include simplifying or enhancing designs and optimizing setup and execution. Other requirements include safety, compatibility with onboard equipment, etc.[15] Additionally, for certification, NASA requires detailed information about the equipment (e.g., design, electrical scheme, safety manual, etc.).[37]

Polysomnography is inconvenient to operate, cumbersome to wear equipment, and seriously interferes with the sleep of astronauts. Although the portable polysomnography monitor is much simpler than the polysomnography, it still interferes with the sleep of astronauts.

While the Actiwatch can be worn for a long time for monitoring and it can reflect the sleep status relatively realistically, the analysis result is also limited due to the single type of data recorded. In recent years, researchers have focused on extracting biosignal data from different parts of the human body through different processing methods, but the lack of relatively uniform standards has led to relatively slow progress in its clinical diagnostic significance.

Photoplethysmography technology may be the next technology that can be used in sleep monitoring in the aerospace field. Although there is room for improvement in terms of convenience, its accuracy and anti-interference ability are comparable to acceleration sensors and may even have surpassed them. If the analysis method can be further advanced, this technology also has the possibility of being applied in the aerospace field. Actiwatch is the benchmark for the application of acceleration sensor technology in the aerospace field. Other types such as capacitive and resistive sensors also have potential value in the aerospace field. The principle is similar to that of acceleration-sensing technology.

There is no case of successful application of infrared biosensing technology in space. Infrared technology may interfere greatly in space and may not be well adapted to the space environment. However, with the continuous development and progress of sensor technology, as well as the gradual improvement of infrared imaging accuracy and anti-interference ability, perhaps infrared technology will one day be applied to the aerospace field. Piezoelectric sensor technology may not be suitable for the aerospace field either. In sleep monitoring, the pressure caused by gravity is used for monitoring, and its main principle is difficult to realize in microgravity. The literature related to

Table II. Comparison of Several Common Sleep Monitoring Integrated Devices.

INTEGRATED EQUIPMENT	RELATED HUMAN BODY SYSTEM	INTRUSIVE	ADVANTAGES	LIMITATIONS
Polysomnography	The nervous system, respiratory system, circulatory system, etc.	very high	"Gold standard", high accuracy and authority, precise sleep staging, microscopic sleep structure analysis, apnea analysis	Need to wear many electrodes and sensors, complex operation, strong physical discomfort, and great interference to normal sleep
Portable Sleep Monitoring System	The nervous system, respiratory system, circulatory system	medium	Average accuracy and authority, can be used in the patient's home, can perform sleep staging analysis and apnea analysis	Need to wear a nasal tube, a small number of electrodes and sensors, moderate sleep disturbance
Pajama	respiratory system, circulatory system	low	Breathing signal detected, perform sleep staging analysis, apnea analysis, less disturbance to sleep	Low accuracy and authority, the recognition rate of apnea is low
Smart Phone	respiratory system, circulatory system	low	Less disturbance to sleep; simple operation and long-term tracking	Low accuracy and authority, poor sleep staging accuracy

bioradar technology is not enough to judge whether it is possible to use it in the aerospace field, but in the high-frequency band, it is more likely to be affected by other high-frequency rays in the universe. Therefore, it may not be suitable for sleep monitoring in the aerospace field.

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