A Review of the Functions, Development, and Future Prospects of Pulse Oximeters

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Abstract. As an essential medical monitoring device, pulse oximeters play a critical role in assessing respiratory health. This paper reviews the functions, development, and future prospects of pulse oximeters, elaborates on the working principles of pulse oximeters, including optical measurement and signal processing technologies. By analyzing the development history of pulse oximeters, it summarizes their advancements in portability, accuracy, and multifunctionality. In response to current challenges in measurement accuracy, the paper explores primary methods for improving precision. Finally, it provides an outlook on the future development directions of pulse oximeters, including high-precision measurement, AI integration, and applications in special environments. A pulse oximeter is a medical device that non-invasively monitors blood oxygen saturation. It has evolved from traditional fingertip models to smarter, more portable, and multi-functional designs, with promising future applications in telemedicine, wearable technology, and chronic disease management.

Keywords: Pulse oximeter, blood oxygen saturation, measurement accuracy, motion artifacts, AI intelligence, portable devices

1. Introduction

As a non-invasive medical monitoring device, pulse oximeters are playing an increasingly important role in clinical and daily health management. Since their inception in the 1970s, pulse oximeter technology has undergone rapid development, evolving from bulky equipment to today's lightweight wearable devices. Accurate measurement of blood oxygen saturation is crucial for evaluating respiratory function, monitoring patient conditions, and early detection of potential health issues.[1]

With the aging population and the rise in chronic respiratory diseases, the demand for blood oxygen monitoring continues to grow. In addition, the COVID-19 pandemic has underscored the significance of pulse oximeters in the context of home health management.[2] Nonetheless, contemporary pulse oximeters continue to encounter various challenges pertaining to measurement accuracy, environmental adaptability, and functional integration. This study aims to systematically review the development history of pulse oximeters, analyze current technological bottlenecks, and explore future development directions, providing insights for the improvement and innovation of pulse oximeter technology.

2. Functions and working principles of pulse oximeters

The core function of a pulse oximeter is to monitor blood oxygen saturation (SpO2), which is the percentage of oxygenated hemoglobin relative to total hemoglobin in the blood. This metric is vital for assessing respiratory function and overall health. A normal blood oxygen saturation level is typically above 95%, and a level below 90% may indicate hypoxia, requiring immediate medical attention.

The working principle of pulse oximeters is based on optical measurement technology, primarily utilizing the differences in light absorption characteristics of oxygenated hemoglobin (HbO2) and deoxygenated hemoglobin (Hb) at different wavelengths. The device typically emits light at two distinct wavelengths: red light (approximately 660 nm) and infrared light (approximately 940 nm). Oxygenated hemoglobin exhibits a higher absorption of infrared light, whereas deoxygenated hemoglobin demonstrates greater absorption of red light. By measuring the intensity changes of these two wavelengths after passing through or reflecting off human tissue, the proportion of oxygenated hemoglobin in the blood can be calculated.[3]

Signal processing is a critical aspect of blood oxygen measurement. The optical signals received by the device contain various noises and interferences, such as motion artifacts and ambient light interference. Advanced algorithms, including adaptive filtering, wavelet transforms, and machine learning, are employed to extract useful physiological signals. These technologies help improve measurement accuracy and reliability, particularly under conditions of motion or low perfusion.

3. Development history of pulse oximeters

The development of pulse oximeters has evolved from large, fixed equipment to portable and wearable devices. Early pulse oximeters were bulky and primarily used in hospital intensive care units. With technological advancements, portable devices such as fingertip and wristband oximeters emerged, enabling blood oxygen monitoring to be widely applied in home and outdoor settings. In recent years, wearable devices like smartwatches and fitness trackers have integrated blood oxygen monitoring functions, further enhancing convenience and popularity.

In terms of accuracy, pulse oximeter technology has continuously advanced. Early devices exhibited significant measurement errors under conditions of motion or low perfusion. Improvements in optical sensors and signal processing algorithms have enabled modern pulse oximeters to better address these challenges. [4] For example, multi-wavelength measurement technology enhances adaptability to different skin tones, while advanced motion artifact removal algorithms significantly improve measurement accuracy during physical activity.

Multifunctional integration represents a significant trend in the evolution of pulse oximeters. Contemporary devices are capable of not only measuring blood oxygen saturation but also monitoring heart rate, blood pressure, sleep quality, and various other physiological parameters. Some high-end devices integrate AI analysis capabilities, providing health recommendations and alerts based on monitoring data. This multifunctional integration not only enhances device utility but also offers users a more comprehensive health management solution.

4. Methods for improving measurement accuracy of pulse oximeters

Improving the measurement accuracy of pulse oximeters is a key focus of current research. Motion artifacts are one of the primary factors affecting measurement accuracy, causing signal distortion and measurement errors. To address this issue, researchers have proposed various

solutions. The VMD-NLMS improved algorithm is an effective method that uses variational mode decomposition (VMD) to decompose photoplethysmography (PPG) signals into multiple intrinsic mode functions (IMFs), followed by normalized least mean squares (NLMS) adaptive filtering to remove motion artifacts. This approach effectively separates physiological signals from motion noise, improving measurement accuracy.[5]

Differences in skin tone and thickness are another factor affecting measurement accuracy. Darker skin and thicker tissue absorb more light, potentially leading to lower measurement results. To address this, researchers have developed multi-wavelength measurement technologies and personalized calibration algorithms. By using more wavelengths of light and establishing personalized calibration curves, the impact of skin tone and thickness on measurement results can be effectively reduced.

Enhancing measurement accuracy under low perfusion conditions is also a research priority. In cold environments or cases of poor blood circulation, signal quality significantly deteriorates. To address this, researchers have developed high-sensitivity sensors and advanced signal amplification technologies. Additionally, machine learning algorithms can extract useful physiological information from weak signals, improving measurement reliability under low perfusion conditions.

5. Future prospects of pulse oximeters

High-precision measurement is an important direction for the future development of pulse oximeters. With continuous advancements in sensor technology and algorithms, future pulse oximeters are expected to achieve higher accuracy and reliability. For example, the development of new optical sensors and the application of deep learning algorithms can further enhance adaptability to various complex conditions. Meanwhile, personalized calibration and adaptive algorithms will enable devices to better accommodate the physiological characteristics of different users.

The integration of AI into pulse oximeters is set to usher in a new era of healthcare monitoring. By leveraging machine learning and big data analysis, these devices will transcend their traditional role of merely providing real-time oxygen saturation and heart rate data. AI algorithms, trained on vast datasets, will be capable of detecting subtle patterns and anomalies in the data, enabling them to conduct sophisticated health risk assessments and predictions. For instance, they could identify early signs of respiratory conditions or cardiovascular issues by analyzing trends over time. Moreover, AI can offer personalized health recommendations, tailored to the individual's unique physiological profile. This level of customization was previously unattainable. Additionally, AI will enhance the device's signal processing capabilities, filtering out noise and interference more effectively, thereby improving measurement accuracy and reliability. This technological leap will make pulse oximeters invaluable tools not just for reactive healthcare but for proactive health management, potentially saving countless lives by addressing health issues before they become critical.[6]

As human exploration and activities expand into more extreme environments, the demand for reliable health monitoring solutions in these challenging conditions grows exponentially. Pulse oximeters, crucial for monitoring blood oxygen levels, must evolve to meet these new demands. In high-altitude environments, where oxygen levels are naturally lower, accurate monitoring is essential to prevent altitude sickness. In deep-sea conditions, where divers operate under high pressure, and in space, where microgravity affects physiological processes, the need for precise oxygen level monitoring is equally critical. Future pulse oximeters will need to be designed with enhanced environmental adaptability, capable of performing accurately under varying pressures, temperatures, and gravitational forces. This will require the development of new sensor materials that can withstand extreme conditions without compromising accuracy. Furthermore, more robust

algorithms will be necessary to compensate for the unique challenges posed by these environments, such as light absorption variations and signal interference. The development of such advanced pulse oximeters will not only ensure the safety of personnel operating in these extreme environments but also pave the way for further human exploration and scientific discovery in previously inaccessible realms.[7]

6. Conclusion

As an essential medical monitoring device, pulse oximeters have made significant progress over the past few decades. From bulky, fixed equipment to today's portable and wearable devices, pulse oximeters have greatly improved in portability, accuracy, and functionality. However, in the face of increasing health monitoring demands and diverse application scenarios, pulse oximeter technology still requires continuous innovation and improvement.

In the future, high-precision measurement, AI integration, and applications in special environments will be the primary directions for the development of pulse oximeters. Through the integration of sophisticated sensor technologies, advanced signal processing algorithms, and artificial intelligence, pulse oximeters are anticipated to attain a higher level of accuracy and intelligence in health monitoring. At the same time, the development of new pulse oximeters for special environments will provide critical support for human exploration of extreme conditions.

In summary, advancements in pulse oximeter technology will not only drive progress in medical monitoring devices but also provide strong support for personal health management and disease prevention. With continuous technological breakthroughs, pulse oximeters are poised to become an indispensable component of future intelligent medical systems, making greater contributions to human health.

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