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Review of Key Technologies in Photoelectric Sensors for Pulse Oximeters

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Abstract. Blood oxygen saturation is a critical physiological parameter for evaluating human cardiopulmonary function and blood oxygen-carrying capacity. Non-invasive pulse oximeters based on the principle of photoplethysmography (PPG) have been widely used in clinical monitoring and home health care due to their simple operation and rapid response. This paper reviews the core technologies of pulse oximeters, focusing on the operating principles of their photoelectric sensor modules, hardware circuit design, key performance indicators, and the challenges they face. The article discusses in detail the differences between transmissive and reflective sensors, as well as the design of key circuits in signal processing such as amplification, filtering, and analog-to-digital conversion. Furthermore, it points out the impact of factors such as motion artifacts, low perfusion, and skin color differences on measurement accuracy. Finally, the future development of oximeters towards intelligence, multi-functionality, and high robustness is prospected. This paper aims to provide a theoretical reference for the design optimization and performance improvement of oximeters.

Keywords: Pulse Oximeter, Photoelectric Sensor, Photoplethysmography (PPG), Signal Processing, SpO_2 Measurement

1. Introduction

Blood oxygen saturation is one of the vital signs crucial in clinical medicine. Although traditional arterial blood gas analysis delivers accurate test results, it is an invasive procedure and does not support continuous monitoring. Since the invention of pulse oximetry technology, non-invasive and continuous SpO_2 monitoring has become a standard configuration in surgical anesthesia, intensive care, and the management of chronic respiratory diseases [1]. In recent years, with the popularity of wearable devices, blood oxygen monitoring has expanded from professional medical scenarios to daily health management and gradually entered public life. The growing user base has raised higher requirements for the accuracy, reliability, and wearing comfort of oximeter measurements [2]. The core of a pulse oximeter is to calculate blood oxygen saturation by detecting the changes in light absorption of human tissues at specific wavelengths through photoelectric sensors. Although the technology is mature, it still faces many challenges in practical applications, such as the interference of motion artifacts (i.e., noise generated in blood oxygen detection signals during movement) on testing, weak measurement signals under low perfusion conditions (i.e., low-temperature states), and

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measurement deviations caused by different skin colors [3]. Therefore, an in-depth understanding of the working principles and design points of photoelectric sensors for oximeters is of great significance for optimizing existing products and developing a new generation of monitoring devices. This paper systematically reviews photoelectric sensors for oximeters from the perspectives of theoretical basis, system composition, key technologies, and challenges.

2. Structural composition of oximeters

2.1. Hardware composition of oximeters

A pulse oximeter (hereinafter referred to as an oximeter) is a medical device used to measure oxygen saturation in blood, usually in a non-invasive manner. A complete oximeter consists of six hardware components: sensor, signal processor, microcontroller, display screen, power manager, and shell interface [4-6].

2.2. Software composition of oximeters

In addition to the hardware part, the "backbone" of an oximeter also includes the software driver part. The software part of an oximeter is mainly responsible for signal processing, data analysis, and user interface management to ensure the accurate and stable operation of the device. The software part of an oximeter is composed of a signal processing algorithm system, data management system, user interaction (UI) interface system, calibration and self-test system, power management system, and alarm system.

3. Working principle of oximeters

3.1. Principle of light absorption

The principle of light absorption is the core principle of blood oxygen detection technology for pulse oximeters. It is a non-invasive technology for real-time measurement of oxyhemoglobin content in blood, whose core is to detect the content of different hemoglobins in blood based on the different light absorption characteristics of oxyhemoglobin and deoxyhemoglobin in accordance with the Lambert-Beer Law.

Ordinary hemoglobin (i.e., deoxyhemoglobin) easily binds to oxygen during oxygen transport to form oxyhemoglobin, and its protein structure changes, eventually showing physical properties different from those of deoxyhemoglobin.

In addition, the Lambert-Beer Law describes the relationship between the intensity attenuation of light and the concentration of the medium and the length of the propagation path when light travels through an absorbing medium, which can be written as the formula:

$$\text{Transmitted light intensity} = \text{Incident light intensity} \times e\hat{}(-\text{Absorption coefficient} \times \text{Concentration} \times \text{Optical path length})$$

It can be seen that the different physical properties of oxyhemoglobin and deoxyhemoglobin give them different absorption capacities for light of specific wavelengths. Experiments have shown that oxyhemoglobin absorbs less light in the red light region (about 660 nanometers) and more light in the infrared light region (about 940 nanometers), while deoxyhemoglobin shows the opposite trend

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[7]. An oximeter calculates the blood oxygen content of the subject by analyzing the significant differences in the absorption rates of the two hemoglobins under red and infrared light.

3.2. Photoplethysmography (PPG) technology

Photoplethysmography (PPG) technology is another foundation for blood oxygen measurement. It is a technology for non-invasive detection of pulsatile changes in the cardiovascular system by optical means. "Photoelectric" refers to detection using light sources and photodetectors, "plethysmography" refers to the blood volume in biological tissues, and "pulse wave" refers to the waveform of periodic changes in blood volume caused by the periodic beating of the heart. Therefore, the application process of PPG technology is to irradiate the pulse with a light source, and the photodetector receives the periodic light intensity signal of periodic changes in blood volume, which is the PPG signal. PPG technology focuses on analyzing the entire waveform signal, while the principle of light absorption focuses on real-time blood oxygen level.

3.3. Analysis of the working process of oximeters

A traditional PPG sensor consists of two parts: a light-emitting diode and a photodetector. The working process of an oximeter mainly includes five stages: light source emission, tissue transmission and dynamic absorption, signal conversion, signal processing and feature extraction, and blood oxygen saturation calculation.

Taking a clip-on or patch-type sensor as an example, two light-emitting diodes of specific wavelengths are installed on one side to emit red light of about 660 nm and near-infrared light of about 940 nm respectively. First, the light emitted by the LED is absorbed and scattered by various human tissues when passing through the wearing area, which is the process of tissue transmission and dynamic absorption.

During signal conversion, the photodetector (usually a photodiode or phototransistor) located on the other side of the sensor receives the transmitted or reflected light attenuated by the tissue and converts it into a weak current signal that changes over time. The detected light intensity signal contains various information such as DC and AC signals: the DC component is a large and stable signal derived from the constant absorption of light by non-pulsatile static tissues such as arterial and venous blood, which has high intensity and relatively stable physiological information; the AC component is the PPG wave, a weak periodic signal caused by arterial blood, usually only 1%-2% of the DC component.

During signal processing, the original analog signal is converted into a digital signal after pre-amplification and analog-to-digital conversion. Designing a pre-amplifier with low noise and high input impedance can ensure the quality of the final digital signal [4]. Subsequently, the digital signal passes through a band-pass filter to remove baseline drift and high-frequency noise, thereby separating a stable DC component and a periodic AC component. The band-pass filter is the core of this process; its low-frequency cutoff frequency can filter out baseline drift caused by respiration, movement, etc., and the high-frequency cutoff frequency can filter out ambient light (such as power frequency interference) and power supply noise [5]. Processing the signals of the red and infrared light channels separately can extract the AC signal amplitude reflecting the amplitude of arterial pulsation and the DC signal amplitude reflecting the overall tissue absorption level.

Finally, the system calculates the ratio of the AC component to the DC component in the two channels respectively, and performs normalization to eliminate the impacts of individual differences such as tissue thickness and skin color, thereby obtaining a key parameter—the ratio R:

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$$R = (ACIR/DCIR)(ACred/DCred)$$

A large number of experimental data calibrations show that the R value is negatively correlated with blood oxygen saturation: when the blood oxygen content is high, arterial blood is redder, absorbs more infrared light and reflects more red light, and the R value is small at this time. The conversion curves or formulas between the R value and the corresponding blood oxygen saturation established through a large number of clinical trials are stored inside the instrument [1,7], and the algorithm converts the calculated R value into the final pulse blood oxygen saturation reading (SpO_2) accordingly [6].

In addition, the AC component can not only be used to calculate the SpO_2 content but also extract heart rate information. The quality of the PPG signal directly affects the accuracy and reliability of the final oximeter measurement [8]. Time-domain analysis (such as peak detection) or frequency-domain analysis (such as Fourier transform) of the PPG AC signal can extract the pulse cycle and further calculate the heart rate. In fact, an oximeter is essentially a combination of PPG technology and intelligent algorithms, whose core is to eliminate common-mode interference by comparing the information of dual-wavelength light sources and finally achieve stable extraction of blood oxygen parameters.

4. Research and analysis of oximeter sensors

4.1. Types and characteristics of sensors

According to the different internal optical path structures and functional designs of sensors, commonly used oximeter sensors can be divided into transmissive, reflective, multi-wavelength, and green-light-assisted types. Their core difference lies in the position of the internal light source and the way of collecting optical signals:

Transmissive sensors adopt the form of opposite emission of red and near-infrared LED light sources. After penetrating human tissues, the light is received by the opposite photodetector. By analyzing the differences in blood absorption of light of different wavelengths, information on the periodic changes of arterial blood volume can be extracted, and then SpO_2 and heart rate can be calculated. This type of optical sensor has high signal intensity, stable optical path, and less interference from ambient light, with a measurement accuracy within ±2%, and is widely used in medical clip-on finger oximeters. However, this type of oximeter is very sensitive to low perfusion conditions and is not suitable for thick tissue detection or continuous motion monitoring [1].

Reflective sensors have the light source and detector on the same side. After entering the skin, the light is scattered by tissues, absorbed by blood, and reflected back to the detector on the same side. Parameter calculation is realized by analyzing the AC and DC components in the reflected light. This type of sensor does not require clamping and is often integrated into wearable devices such as smart watches and smart bracelets, suitable for long-term continuous real-time monitoring. However, its disadvantage is that the intensity of the reflected signal is weak, the received signal is greatly affected by the environment, and the measurement accuracy is usually about ±3–5% lower than that of the transmissive type. The error will be greater especially in motion or low perfusion scenarios. Noise similar to the frequency of the pulse signal generated during movement and the reduced PPG signal amplitude caused by low blood flow at low perfusion during low perfusion will interfere with the useful signal [1-3].

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Multi-wavelength sensors expand bands such as green light, blue light, or additional near-infrared light on the basis of traditional dual-wavelength sensors, which can more accurately distinguish oxyhemoglobin, deoxyhemoglobin, and some abnormal hemoglobins such as carboxyhemoglobin, and can greatly improve detection accuracy and anti-interference ability under complex physiological conditions. Multi-wavelength optical sensors often adopt more advanced signal processing algorithms and are mostly used in high-standard and high-requirement medical scenarios such as intensive care and operating rooms.

Green-light sensors mainly use green light sources in the 510–590 nm band. Light of this wavelength is more sensitive to changes in superficial blood flow than other wavelengths, and is commonly used for heart rate monitoring. It can also be used as an auxiliary signal light for red/near-infrared systems to improve the stability of heart rate detection in human motion states. Since green light is not obvious for hemoglobin detection, this type of sensor cannot be directly used for blood oxygen measurement. However, due to its low power consumption and strong anti-motion interference ability, it is often used in dynamic heart rate monitoring devices such as fitness bracelets.

4.2. Analysis of key performance indicators

The performance of an oximeter sensor directly determines the accuracy and reliability of the final measurement results. The core indicators of oximeters will be analyzed in detail combined with different types of sensors below:

The measurement accuracy of the sensor is evaluated based on the deviation between the SpO_2 and heart rate test results and the gold standard such as arterial blood gas analysis. Usually, the accuracy of medical transmissive sensors is within ±2% (SpO_2 range 70–100%), while reflective sensors are limited by signal quality, with an accuracy limit of about ±3–5%. Due to the rich spectral information, the accuracy of the multi-wavelength system can reach ±1% or even higher. Sensitivity reflects the sensor's ability to capture weak blood flow signals, usually expressed by the lower limit of the Perfusion Index (PI). Sensors of high-end medical oximeters can detect weak perfusion as low as 0.02% PI. Factors affecting the detection accuracy and sensitivity of the sensor include the purity of the light source spectrum, the response characteristics of the photodetector, the skin pigment and thickness of the tested tissue of the subject, the interference of motion artifacts during detection, and the efficiency of the signal processing algorithm inside the instrument.

Signal-to-Noise Ratio (SNR) refers to the strength ratio between the useful pulsatile signal and background noise that directly determines the distinguishability and stability of the signal. Due to the closed optical path and strong signal, the SNR of transmissive sensors is generally higher than that of reflective sensors. Anti-interference ability involves the performance of suppressing the impacts of factors such as human movement, ambient light, low perfusion environment, and skin interface changes on the results. Reflective sensors are easily affected by external light and poor fitting, and need to rely on optical shielding and adaptive filtering algorithms to enhance stability, such as motion compensation. By acquiring and analyzing multi-spectral redundant information, multi-wavelength systems can still effectively distinguish physiological signals from noise and maintain high reliability during low perfusion or patient movement.

Response time refers to the time required from signal collection to stable output of results, usually 3 to 8 seconds. For emergency and critical care, high-frequency sampling and HEPA high-efficiency algorithms can be used to shorten the response time to within 3 seconds. Sensor power consumption directly affects the battery life of the device. Intermittent sampling, use of low-power photodetectors, and optimization of LED driving strategies are common methods for consumer-

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grade wearable devices to extend service time. Due to the compact circuit structure and low driving current, reflective and green-light sensors have certain advantages in low power consumption, and their smaller size is also convenient for portability, suitable for battery-powered use.

Sensors still need to maintain stable working performance in possible real-life environments such as different temperatures (0–50 ℃), humidity, and light changes. Medical oximeters need disinfection and other treatments due to the particularity of the use environment, and their internal sensors often have characteristics such as disinfection resistance, dustproof and waterproof (such as IP67), and anti-aging. The size and integration of the chip determine the application form of the sensor. Smaller reflective and green-light sensors can be applied to smart watches or patch-type oximeter detection devices; larger transmissive sensors are mostly used in clip-on finger independent devices. According to the development of the electronic chip field, the research and development of highly integrated sensor modules capable of simultaneous measurement of multiple parameters such as blood oxygen, heart rate, body temperature, and respiration with the help of MEMS technology and flexible electronics is the future trend.

4.3. Sensor design optimization based on simulation

With the development of blood oxygen sensors towards high performance such as miniaturization, low power consumption, and high accuracy, the traditional trial-and-error method for iteration in the sensor design field still faces challenges of low design efficiency and high design cost. With the development of modern industrial software, the emergence of computer simulation technology provides a new idea for sensor design, and efficient simulation software is a powerful tool for theoretical analysis and sensor design optimization. This section will focus on how to use COMSOL Multiphysics, a simulation software, to simulate and analyze the optical structure and signal transmission characteristics of blood oxygen sensors, and guide the optimization process of sensor design by analyzing simulation results.

4.3.1. Basic simulation modeling and key parameter setting

It is known that the working principle of oximeter sensors relies on two theories of light transmission in biological tissues: the principle of light absorption and Photoplethysmography (PPG) technology, and optical simulation can be carried out using COMSOL. The interaction between light and tissues mainly includes three forms: absorption, scattering, and reflection. The entire optical process can be described by the Radiative Transfer Equation (RTE) or its approximate form (such as the diffusion equation). For this purpose, several parameters for the transmission equation or diffusion equation need to be defined in COMSOL modeling:

First, it is necessary to determine the absorption coefficient (μa), scattering coefficient (μs), anisotropy factor (g), refractive index (n) of tissue optical properties, and the absorption coefficients of various anisotropic factors. These parameters are the basis for determining the simulation accuracy and are closely related to the wavelength length. For the modeling and analysis of oximeter sensors, a skin tissue layered model (such as epidermis, dermis, subcutaneous tissue, etc.) is usually directly used to simulate the use scenario of the sensor, which can be established from open-source information or experimental measurements. Second, it is necessary to define the geometric size, divergence angle, wavelength (600 nm red light and 940 nm infrared light can be used), output power, and spatial distribution mode (such as Lambertian) of the light source to determine the model of the light source module. Then, it is necessary to define the active area, relative position, spectral responsivity, and photodetector sensitivity of the photodetector (taking photodiode as an example).

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Finally, it is necessary to accurately establish a three-dimensional geometric model of the sensor probe, including the layout of the LED light source and photodetector, relative distance (especially important in reflective type), material of the optical window, and possible filters or optical isolation structures.

4.3.2. Key simulation content and analysis of simulation results

After determining the key parameters, simulation can be carried out using the "Wave Optics" or "Ray Optics" module of COMSOL combined with the "Optimization" module to evaluate the following core performances:

First, a transmissive or reflective sensor model can be established to simulate the optical energy flow rate distribution (i.e., photon density) inside the tissue under the irradiation of a specific wavelength light source, thereby analyzing the sensor sensitivity distribution and detection depth. The "detection depth" and "sampling volume" of the sensor can be quantified by analyzing the contribution ratio of different depth regions to the signal received by the detector, which helps to optimize the spacing between the light source and the detector in the reflective sensor and achieve the best balance between signal intensity and sensitivity to arterial pulsation. Simulation can intuitively show that when the spacing is too small, it is greatly affected by venous blood and skin pigment interference, and the main sampling is epidermal signal, while an excessively large spacing will weaken the signal during long-distance sampling.

Key design variables affecting SNR can be analyzed through parametric scanning and optimization research. When simulating ambient light (such as fluorescent lamps, sunlight) incident from different angles, the geometry of the light shield and the light trap structure can be optimized accordingly according to the stray light intensity on the detector, which can greatly suppress the interference of ambient light. For reflective sensors, the relative position and array arrangement of the light source and detector (such as multi-light source-single detector or circular layout) can be systematically changed, and then the ratio of the received pulsatile signal (AC component) intensity to the background tissue signal (DC component) can be simulated and calculated to maximize the SNR by finding the optimal layout. To explore the impact of skin contact on the sensor and provide a basis for flexible patch design or contact pressure feedback, the optical path change when there is an air gap or sweat layer between the sensor and the skin can be simulated to evaluate the signal attenuation degree.

To evaluate the impact of skin color and tissue heterogeneity, the optical property differences can be simulated by modifying the absorption and scattering parameters of different skin layers in the simulation model, simulating the difference from light to dark skin types. Analyzing the detected light intensity, signal attenuation, and pulsatile component changes of the same sensor designed under different skin color models can quantify the possible systematic errors introduced, providing important prior data for the research and development of sensors with skin color adaptive calibration algorithms, guiding the wavelength selection of multi-wavelength schemes, and optimizing power ratio.

Finally, the power consumption and thermal effect of the sensor can be analyzed by coupling the "Joule Heat" or "Solid Heat Transfer" module of COMSOL with optical simulation. By simulating the luminous efficiency of LEDs under different driving currents, the optical power radiated to the tissue, and the generated heat, the temperature rise of the sensor during long-term operation can be evaluated, which helps to optimize the driving strategy to achieve the lowest power consumption on the premise of ensuring sufficient signal intensity, and ensure thermal comfort and biological safety, especially for wearable devices for continuous monitoring.

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4.4. Simulation-guided optimization design process

To study the sensor optimization scheme based on simulation, the geometric model and optical model of the sensor should be modeled according to real-life applications and correct wearing requirements. Second, it is necessary to determine the optimization objectives (such as maximizing sensitivity at a specific depth, maximizing SNR, minimizing power consumption) and design various variables such as LED-detector spacing, LED emission angle, and light shield angle as key modeling parameters. After setting the parameters, parametric scanning should be carried out to study the impact of a single variable on the performance indicators and identify sensitive parameters. Then, the built-in optimization algorithms of COMSOL (such as gradient method, global search method) are used to collaboratively optimize multiple design variables and find the Pareto optimal solution set under given constraints such as size limit and maximum power consumption. Finally, the optimal design scheme is made into a physical prototype for real experiments, and the test results are compared with the simulation predictions to calibrate and correct uncertain factors such as tissue optical parameters in the simulation model for a more accurate round of simulation optimization.

5. Current status and dilemmas of oximeter sensors

5.1. Current status of product optimization

So far, oximeters mostly adopt multi-wavelength LED light sources (such as adding green light) in hardware to provide more body information or enhance the anti-interference ability of signal detection. More sensitive detectors are also used, or the physical structure and wearing mode of the probe are optimized to ensure better contact between the human body and the oximeter and reduce the intrusion of ambient light [2]. In terms of sensor design, the market development direction is committed to integrating the analog front-end, ADC, and even microprocessor into a single chip to make it a dedicated oximetry analog front-end, which helps reduce the size of the sensor, lower power consumption, and improve system consistency [4]. In terms of software, the development of more advanced signal processing algorithms is a current research hotspot. The use of adaptive noise cancellation, blind source separation, and model algorithms based on machine learning or deep learning can also more effectively separate pure and stable PPG signals from noise, thereby improving the performance of oximeters in challenging application scenarios such as movement and low temperature [6].

5.2. Technical development bottlenecks

Although blood oxygen measurement technology is becoming increasingly mature, current oximeters still face multiple technical bottlenecks in accuracy improvement, hardware integration, algorithm optimization, and other aspects, which limit their application and development in a wider range of scenarios.

When traditional red/near-infrared sensors deal with problems such as dark skin, pigmentation, or low perfusion in hypothermic shock, the penetration or reflection intensity of optical signals will be significantly lower than that under normal conditions, leading to a decrease in SNR and measurement deviation of the system. In addition, external factors such as motion artifacts and nail coating will further interfere with signal collection, making it difficult for existing algorithms to achieve high-precision data calibration for different groups of people. There are precedents where

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patients with extended nails cannot wear clip-on finger oximeters, making it impossible to detect vital signs and affecting rescue. The absorption of light by melanin weakens the light intensity reaching the detector, which is equivalent to increasing the DC component of the real data, which may affect the calculation of the R value and lead to low measurement results for people with dark skin [9]. Although multi-wavelength light source technology is expected to improve the use effect for people of different skin colors, its optical modeling is more complex than that of red/near-infrared sensors, with high research and production difficulty, and has not been popularized in consumer-grade devices. Household and wearable oximeters pursue portability and comfort more, but an excessively small sensor size will lead to SNR loss; medical high-precision equipment faces challenges of excessive power consumption and cost due to high requirements for multi-light sources and high sampling rate design.

At present, the research and development speed of flexible optoelectronic materials and low-power chips still lags behind the high-performance demand of the modern market for oximeters, which greatly limits the battery life and detection stability of wearable devices in continuous monitoring scenarios. At the same time, the performance of oximeters highly depends on the computing power and energy efficiency of core chips, and the existing chip technology is not sufficient to fully support the long-term, real-time, and continuous high-precision data processing requirements of sensors.

The traditional simplified algorithm based on the Lambert-Beer Law is difficult to accurately analyze optical signals under complex physiological states. Although the rapid development of modern artificial intelligence provides new solutions and ideas for signal denoising, feature extraction, and abnormal recognition functions, its model training requires a large number of real clinical data sets for support. Currently, such data sets still have problems such as limited scale, and the data sets belong to personal physical information, and their collection process involves the privacy protection of patients. In addition, there are certain ethical issues in collecting data sets of non-normal health attributes, which also have certain limitations.

6. Conclusion and prospect

This paper systematically sorts out the key technologies of photoelectric sensors for oximeters and finds that its working core lies in efficiently capturing high-quality PPG signals through internally designed hardware facilities, and then accurately extracting SpO_2-related information from noise through internally set algorithms. At present, blood oxygen measurement technology is developing in two main directions: one is miniaturized, low-power, and highly integrated wearable devices for daily consumer-grade applications; the other is professional monitoring equipment with high processing accuracy, multi-parameter data, and high robustness (i.e., high anti-interference) for medical detection-grade applications. Future research will focus more on solving technical problems such as motion artifacts and low perfusion through artificial intelligence algorithms and models, improving the universality of the same measuring device for different groups of people, and loading an intelligent system for oximeters. At the same time, combining blood oxygen monitoring with other physiological parameter monitoring functions such as heart rate analysis and blood pressure detection to design multi-functional health monitoring products is the core of future development. With the continuous progress of modern technologies such as sensing technology, semiconductor technology, and algorithm capability, blood oxygen monitoring technology will play an increasingly important role in precision medicine and personal health management. Perhaps in the future, the research and development of multi-functional intelligent oximeters that can simultaneously meet medical and personal needs will no longer be a possibility.

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