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Heart rate sensors: technologies, measurement principles, signal processing, and applications a review

Tole Sutikno[1], Suardi[1], Zakky Ahmad Ikhsan[2]
[1]Faculty of Industrial Technology, Universitas Ahmad Dahlan, Yogyakarta, Indonesia
[2]Institute of Advanced Engineering and Science, Yogyakarta, Indonesia

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ABSTRACT

Heart rate (HR) is a fundamental physiological indicator used in exercise assessment, clinical observation, and long-term health monitoring. Conventional measurement relies on electrocardiography (ECG), whereas wearable systems increasingly use photoplethysmography (PPG), which estimates pulse rate from optical changes associated with peripheral blood-volume variation. This review examines operating principles, sensor architectures, signal-processing methods, applications, and limitations of contact and contactless HR technologies reported up to 2019. Particular attention is given to ECG electrodes, wrist-worn reflective PPG, smartphone measurements, and remote PPG imaging, emphasizing trade-offs among accuracy, comfort, power consumption, and usability. The literature indicates that ECG remains an important reference for cardiac electrical activity, while PPG offers a practical route to unobtrusive monitoring. However, movement, sensor placement, skin perfusion, ambient illumination, and individual physiological differences can degrade PPG-derived estimates. Motion-aware filtering, multi-wavelength sensing, signal-quality assessment, and validation against ECG can improve reliability, although performance varies across activities and populations. The review identifies the need for standardized testing, uncertainty reporting, and privacy-aware data handling before consumer devices can be treated as clinical substitutes. Overall, integrated sensing and robust signal interpretation are central to dependable everyday HR monitoring.

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1. INTRODUCTION

Heart rate (HR), commonly expressed in beats per minute (bpm), is an important physiological parameter for evaluating cardiovascular response and general physical condition. It is routinely used in clinical observation, exercise monitoring, rehabilitation, and personal health applications. Conventional measurement methods have relied on electrocardiography (ECG), pulse oximetry, and manual pulse assessment. Recent developments in wearable electronics have expanded HR monitoring beyond hospitals and laboratories into everyday environments [1]–[3].

The growing demand for continuous monitoring has encouraged the development of compact, low-power, and user-friendly sensors. Wrist-worn devices commonly employ photoplethysmography (PPG), while chest straps and smart garments may use ECG electrodes to capture cardiac electrical activity. Camera-based systems have also demonstrated the possibility of estimating pulse rate without direct skin contact. These approaches offer different combinations of accuracy, comfort, cost, and practical usability [4]–[8].

Despite technological progress, reliable HR measurement remains challenging under real-world conditions. Sensor movement, poor skin contact, changing illumination, low peripheral blood perfusion, and individual physiological differences can distort the measured signal. Furthermore, a pulse-rate estimate is not identical to a direct measurement of cardiac electrical activity, which is particularly important when interpreting irregular rhythms. This review therefore examines the main HR sensing technologies, their signal-processing requirements, practical applications, and research challenges.

2. RESEARCH PROBLEMS AND SCOPE

The central research problem in HR sensing is the need to obtain accurate and continuous measurements without imposing excessive discomfort or restricting normal activity. ECG-based systems provide information about the electrical events associated with cardiac contraction, but conventional electrodes may be inconvenient for long-term everyday use. Optical PPG sensors are easier to integrate into consumer wearables, although their signals are susceptible to motion and changes in peripheral circulation. Consequently, sensor selection must consider both the intended application and the conditions under which measurements will be collected [7]–[9].

A second problem concerns the interpretation and validation of sensor output. Different devices may use different sampling rates, filtering methods, measurement locations, and averaging intervals, making direct comparisons difficult. A device that performs well during rest may produce less reliable results during walking or intensive exercise. This review focuses on the sensing and engineering aspects of HR measurement rather than attempting to establish clinical diagnostic criteria.

3. HEART RATE SENSOR TECHNOLOGIES

3.1. Electrocardiography-based sensors

ECG sensors measure the electrical potential generated by the heart and recorded through electrodes placed on the body surface. The resulting waveform contains recognizable features, including the QRS complex, which is commonly used to identify individual cardiac cycles and calculate HR. ECG is valuable because it provides information about cardiac electrical activity rather than relying solely on peripheral pulse detection. Its measurement principle makes it an important reference technique for evaluating other HR monitoring technologies [1], [7].

Wearable ECG systems have evolved from conventional adhesive electrodes toward dry electrodes, textile-based electrodes, and smart garments. Textile electrodes can be incorporated into clothing, potentially improving comfort and supporting long-term monitoring without conventional conductive gel. Research on conductive textile materials has demonstrated their potential for recording ECG signals during rest and physical activity [4]. Nevertheless, electrode placement, skin contact pressure, moisture, and body movement can influence signal quality [10].

3.2. Photoplethysmography-based sensors

PPG is an optical technique that detects changes in blood volume within peripheral tissue. A typical sensor contains a light-emitting diode and a photodetector, which measures variations in transmitted or reflected light associated with the cardiac pulse. The resulting waveform contains a pulsatile component related to blood-volume changes and a slowly varying baseline influenced by physiological and environmental factors. PPG is attractive for wearable applications because it is non-invasive, relatively inexpensive, and suitable for compact electronic devices [3], [9].

Two common PPG configurations are transmissive and reflective sensing. In transmissive systems, light passes through tissue and is detected on the opposite side, as commonly implemented in fingertip pulse sensors. Reflective systems position the light source and detector on the same side of the tissue, allowing integration into wristbands and smartwatches. Wrist-worn reflective PPG has become particularly important because it supports continuous measurement without requiring users to wear chest electrodes [8].

3.3. Camera-based and remote sensors

Remote photoplethysmography (rPPG) estimates cardiovascular pulse information from subtle changes in skin color captured by a camera. Unlike conventional PPG, this technique does not require a sensor to be attached directly to the skin. Early research demonstrated that ambient-light video could reveal periodic variations associated with cardiac activity [2]. Later work developed practical imaging methods and software approaches that enabled HR estimation using ordinary cameras [11].

Smartphones have also become potential platforms for HR monitoring. Some applications use the camera and its illumination source to obtain contact PPG signals, while others employ external ECG accessories or connected wearable devices. These approaches may increase access to basic physiological monitoring because they use widely available consumer electronics. However, application performance depends on camera characteristics, user handling, software processing, and the quality of the recorded signal [12].

4. SIGNAL PROCESSING AND MEASUREMENT ACCURACY

Signal processing is essential because raw physiological signals often contain noise and artifacts that interfere with accurate HR estimation. In ECG systems, baseline drift, power-line interference, muscle

activity, and electrode movement can obscure important waveform features. In PPG systems, motion artifacts are particularly problematic because changes in sensor position and tissue pressure can produce signal components that overlap with the cardiac pulse. Effective preprocessing and signal-quality assessment are therefore necessary before estimating HR [8], [13], [14].

Several approaches have been investigated to improve PPG signal quality during movement. Adaptive filtering, wavelet processing, frequency tracking, and motion-reference techniques can help distinguish cardiac components from unwanted disturbances. Multi-wavelength sensing has also been explored to improve motion-artifact reduction by using signals recorded at different optical wavelengths. These approaches indicate that sensor hardware and signal-processing algorithms should be designed as complementary components rather than independent solutions [13]–[15].

Measurement accuracy also depends on the experimental conditions and validation procedure. Studies comparing PPG devices with ECG have reported that performance can vary between rest, exercise, and daily-life activities. The measurement location, device fit, activity intensity, and averaging period can all affect the observed agreement. Therefore, validation should include representative activities and an appropriate reference instrument rather than relying exclusively on stationary laboratory measurements [5], [6], [16].

5. APPLICATIONS OF HEART RATE SENSORS

HR sensors are widely used in fitness monitoring and exercise management. Wearable PPG devices allow users to observe changes in pulse rate during walking, running, cycling, and other physical activities. Such information can support exercise intensity assessment and provide feedback during training. However, users should recognize that measurement errors may increase during vigorous movement, especially when the optical sensor is poorly positioned [5], [8], [17].

In healthcare, continuous HR monitoring can support patient observation and remote health management. ECG-based wearable systems are particularly relevant when electrical cardiac information is required, while PPG devices provide a convenient means of tracking peripheral pulse rate. Smartphone-based applications may also contribute to preliminary monitoring and data collection outside conventional clinical environments. Nevertheless, consumer devices should not automatically be considered substitutes for clinically validated diagnostic equipment [7], [12].

6. CHALLENGES AND FUTURE RESEARCH DIRECTIONS

One major challenge is maintaining measurement accuracy across different users and operating conditions. Skin perfusion, temperature, sensor pressure, movement, and anatomical differences can influence optical signal quality. Wearable devices must therefore be evaluated across diverse populations and activities to establish the limits of their performance. Future designs should provide clear indications when signal quality is insufficient for reliable HR estimation [8], [13], [16].

Another challenge concerns the balance between sensor performance and user comfort. ECG systems can provide valuable electrical information, but electrode contact and garment design may affect long-term acceptance. PPG devices are convenient, although their dependence on peripheral blood-flow signals introduces limitations under certain physiological conditions. Hybrid systems combining ECG, PPG, and motion sensors may provide more robust monitoring by exploiting complementary information from different sensing modalities [4], [7], [10].

Future research should also address standardization, energy efficiency, and data privacy. Comparable validation protocols are needed to make performance claims across devices and studies more meaningful. Low-power processing and efficient algorithms will be important for extending battery life in continuously operating wearable systems. In addition, personal physiological data should be protected through appropriate security and privacy practices, particularly when measurements are transmitted to smartphones or cloud-based services [8], [12], [18].

7. CONCLUSION

Heart rate sensing has developed from conventional ECG measurement into a broad range of wearable, smartphone-based, and contactless technologies. ECG remains an important method for monitoring cardiac electrical activity, whereas PPG offers a practical and comfortable approach to estimating pulse rate in everyday environments. Camera-based rPPG further demonstrates the potential of non-contact monitoring, although its performance remains sensitive to imaging conditions and subject movement. Each technology therefore has distinct advantages and limitations that should be considered when selecting a sensor for a particular application. The reviewed literature shows that reliable HR monitoring depends not only on sensor design but also on signal processing, measurement conditions, and appropriate validation. Motion artifacts,

contact quality, physiological variation, and inconsistent evaluation procedures remain important barriers to dependable real-world performance. Future systems should combine suitable sensing modalities with robust algorithms, transparent signal-quality indicators, and standardized validation procedures. With these improvements, HR sensors can provide increasingly useful support for personal wellness, exercise monitoring, and selected healthcare applications.

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