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# *Recent Advances in Flexible Sensing and Edge Intelligence for Embedded Medical Devices: Challenges in Clinical Translation*

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***Abstract.*** Enabled by chronic disease management, aging trends, and digital health, medical monitoring is evolving from intermittent testing to continuous personalized monitoring. In this context, embedded medical devices integrate physiological data acquisition with edge computing technologies. This review examines the development of flexible sensing and edge intelligence approaches in embedded medical devices, with a focus on their progression from physiological signal acquisition to intelligent analysis and clinical translation. By analyzing recent advances in related technologies, this review summarizes key developments in sensing materials, device architectures, on-device computing, and system-level integration, while also identifying challenges associated with long-term stability, power efficiency, data security, and clinical validation. The analysis highlights that future progress will rely on the synergistic optimization of device design, intelligent algorithms, and clinical evaluation frameworks, with low-power intelligence, multifunctional integration, and standardized evaluation as key directions for future development.

***Keywords:*** Embedded medical devices, Flexible sensing, Multimodal sensing, Edge intelligence, Physiological monitoring, Clinical translation

## 1. Introduction

The growing demand for chronic disease management, aging populations, and remote healthcare services is accelerating the transition of medical monitoring from episodic clinical measurements to continuous and personalized monitoring [1]. This shift has created new demands for medical devices, which must not only acquire physiological information reliably but also provide long-term wearing comfort and adapt to daily human activities. However, traditional medical devices are usually based on rigid sensing elements and centralized processing architectures, which limit their applicability for continuous monitoring beyond clinical settings. To overcome these limitations, embedded medical devices require improved human-machine compatibility, efficient physiological data acquisition, and localized data processing capabilities. Thus, flexible sensing and intelligent embedded systems have become key approaches for continuous physiological monitoring [2, 3]. Despite these advances, technological progress alone does not guarantee successful clinical

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translation. In practice, long-term-used devices require stable sensing performance under physiological and environmental variations. At the same time, continuous physiological data processing poses higher requirements for computing efficiency, power consumption, data security, and system integration. Under these circumstances, these challenges hinder the transition from laboratory performance to clinical use. Therefore, this study focuses on the development of flexible sensing and edge intelligence technologies in embedded medical devices and explores how these technologies can meet the needs of continuous physiological monitoring. Additionally, it further identifies main barriers limiting clinical translation, including reliability, power consumption, data security, standardization, and system integration.

## 2. Emerging needs and enabling technologies for embedded medical devices

### 2.1. Continuous monitoring needs and the evolution of medical devices

With the expansion of healthcare monitoring beyond conventional clinical settings into real-world environments, medical devices are evolving from intermittent diagnostic tools toward continuous and personalized monitoring systems. Accordingly, embedded medical devices must meet application demands beyond conventional equipment. In particular, reliable long-term acquisition of clinically relevant physiological signals is required to track individual health changes across varying time periods and activity conditions [1]. Beyond sensing performance, long-term use requires improved human-device compatibility and user comfort to minimize interference with daily activities. At the same time, continuous monitoring generates large volumes of high-frequency physiological data, creating new requirements for efficient data processing and timely health assessment.

### 2.2. Physiological sensing requirements and information acquisition

Effective continuous health monitoring requires reliable acquisition of physiological signals under diverse daily conditions. In real-world settings, continuous variations in body movement, posture, activity intensity, and physiological state can significantly influence signal quality and measurement stability [2]. As a result, sensing devices for continuous monitoring must maintain accurate and consistent physiological signal acquisition over extended periods rather than relying on short-term measurements at specific time points.

Traditional medical monitoring approaches are often optimized for episodic assessment in clinical settings, where signal acquisition conditions are relatively stable and external disturbances can be minimized. However, their limited adaptability to daily activities restricts their ability to capture dynamic physiological changes during long-term use. Besides, continuous health monitoring requires not only accurate signal acquisition but sufficient user acceptance to support frequent or prolonged interaction with monitoring devices. These requirements highlight the need for advanced sensing approaches capable of supporting reliable, continuous, and user-compatible physiological monitoring.

### 2.3. Data analytics requirements and intelligent processing technologies

Through long-term acquisition of time-series physiological data, continuous monitoring introduces new requirements for data processing and interpretation. Unlike intermittent clinical measurements, continuous monitoring captures temporal variations in physiological states, thus resulting in

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complex datasets that are difficult to analyze via manual review or conventional rule-based methods. Moreover, physiological signals are influenced by individual variability and changing conditions, thus making it challenging to distinguish clinically relevant patterns from large amounts of monitoring data [4].

Accordingly, these characteristics necessitate data processing approaches capable of extracting meaningful information from continuously acquired physiological signals. Beyond data acquisition, embedded medical devices require effective analysis methods to support timely health assessment and facilitate clinical decision-making. Furthermore, the growing complexity of physiological data emphasizes the need for improved processing efficiency and analytical capabilities in continuous monitoring systems.

## 3. Flexible sensing and intelligent processing technologies for embedded medical devices

### 3.1. Flexible sensing and physiological information acquisition

To support long-term physiological monitoring with improved adaptability and stability, flexible sensing technology has become a key approach for embedded medical devices [5]. The development of flexible sensing involves addressing multiple challenges associated with long-term physiological monitoring, including stable body-sensor interaction, mechanical adaptability, device integrity, and functional integration. Flexible electrodes mainly improve the contact interface between the human body and the sensor to boost the stability of physiological signal collection. However, reliable signal acquisition requires not only improved interface adaptation but also conductive structures capable of maintaining electrical performance under repeated deformation. Therefore, liquid metals, due to their excellent conductivity and deformable properties, offer an alternative material option for stretchable conductive structures. Beyond conductive components, flexible substrates support sensing devices and accommodate deformation during human movement while maintaining structural stability.

Building on these advances, electronic skin further extends flexible sensing by integrating multiple sensing functions into a unified platform, enabling simultaneous monitoring of physiological signals and motion-related information [3, 6]. Through this transition from interface adaptation to conductive structures, device support, and multifunctional integration, medical sensors have transformed from rigid single-function components into flexible multifunctional platforms with improved comfort and signal reliability. However, challenges in material durability, long-term stability, and multifunctional integration remain for clinical applications.

### 3.2. Multimodal sensing and physiological data fusion

In complex physiological conditions, a single physiological parameter is often inadequate to capture comprehensive health information. Therefore, embedded medical devices are increasingly shifting from single-parameter sensing toward multimodal physiological perception to obtain complementary information from different aspects of human health. By integrating diverse sensing modalities, such as electrical, physiological, mechanical, and chemical signals, these devices can capture physiological states from multiple dimensions and provide comprehensive health information [7].

However, multimodal sensing introduces new challenges in data fusion, as signals from different sources often exhibit distinct formats, temporal resolutions, and response characteristics. Therefore, effective fusion of heterogeneous physiological data is required to identify meaningful relationships

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among different parameters and enhance the reliability of health assessment. Beyond individual signal analysis, multimodal data fusion combines complementary signals from multiple sources to improve physiological assessment. These requirements highlight the importance of efficient fusion strategies for embedded medical systems to achieve comprehensive and reliable health monitoring.

### 3.3. Edge intelligence and real-time medical data processing

The increasing complexity of physiological data and the demand for real-time health assessment have accelerated the integration of edge intelligence into embedded medical devices. Unlike conventional cloud-based processing, edge intelligence enables part of the data analysis to be performed closer to the sensing unit, reducing data transmission requirements and improving response efficiency [8]. To support intelligent processing under limited power and computational resources, embedded medical devices increasingly adopt low-power processors and optimized computing architectures for local data handling.

In addition, model compression techniques reduce the computational and storage requirements of intelligent models, enabling their deployment on resource-constrained devices. Combined with on-device artificial intelligence (AI) inference, these approaches allow physiological data to be processed locally while maintaining timely analysis capabilities [4]. Compared with transmitting large volumes of raw data to remote servers, local processing can reduce communication latency and enhance the protection of personal health information privacy. The integration of low-power computing, model optimization, and device-side inference therefore provides a practical pathway toward real-time and privacy-aware medical monitoring.

## 4. Barriers to clinical translation and optimization approaches for embedded medical devices

### 4.1. Clinical validation and reliability assessment

During prolonged operation in real-world environments, embedded medical devices are continuously exposed to mechanical deformation, sweat, temperature variation, and daily activities, which may affect material stability and cause signal drift or performance degradation over time [3, 9]. These factors can accumulate during prolonged use, making it challenging to maintain consistent sensing accuracy and device reliability under realistic conditions. In real-world settings, additional variability in physiological states, user behaviors, and environmental conditions may further widen the gap between experimental performance and practical monitoring outcomes. For devices designed for continuous contact with the human body, biocompatibility and user safety are also critical for reliable long-term operation.

In addition, laboratory-based evaluations often focus on short-term performance under predefined conditions and may not fully capture device behavior during extended clinical use. Comprehensive validation under diverse usage scenarios is therefore necessary to evaluate long-term stability, signal reliability, and practical applicability. Further improvements in reliability assessment and real-world clinical validation are required to bridge the gap between laboratory-level performance and clinical deployment.

### 4.2. Data security and regulatory compliance

Driven by continuous monitoring and AI-based analysis, clinical applications require stronger data privacy protection, secure management, and regulatory compliance [8]. The continuous collection,

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storage, and transmission of physiological information raise concerns regarding data access, security control, and responsible data use, particularly when devices are used in long-term health monitoring scenarios.

Meanwhile, the lack of unified standards for embedded medical devices also limits their clinical translation. Differences in sensing mechanisms, data formats, calibration methods, and evaluation criteria limit device comparison across studies and standardized assessment [6]. Thus, standardized requirements for data management, performance evaluation, and clinical assessment are needed to improve reproducibility, support regulatory evaluation, and facilitate the adoption of embedded medical technologies. Such requirements also influence the evaluation and deployment of embedded medical devices in clinical environments.

### 4.3. Power efficiency and system integration for long-term deployment

The increasing energy requirements associated with continuous sensing, wireless communication, and on-device processing impose substantial challenges for the long-term operation of embedded medical devices. Battery capacity limitations and device miniaturization requirements create a trade-off between operational lifetime, system size, and functional capability. Meanwhile, the integration of sensing, computing, communication, and power management modules within compact platforms increases system complexity and requires efficient coordination among different components [10].

In response to these challenges, system-level optimization strategies improve energy efficiency and integration capability. In particular, low-power edge intelligence reduces unnecessary data transmission and computational costs via local processing, while multifunctional sensing platforms and flexible sensor networks enable compact integration of sensing capabilities. The combination of these approaches supports extended operational lifetime, reduced system complexity, and more reliable long-term deployment of embedded medical devices.

## 5. Conclusion

This review summarizes the development of embedded medical devices by examining flexible sensing, multimodal physiological information acquisition, and edge intelligence technologies, with a focus on their roles in enabling continuous and personalized health monitoring. The analysis indicates that flexible sensing improves human-device compatibility and long-term signal acquisition, multimodal sensing enhances physiological information representation through complementary data integration, and edge intelligence supports efficient local processing for real-time health assessment. However, this review is limited by the rapid evolution of related technologies and the lack of fully standardized evaluation frameworks across different device platforms, which may influence direct comparison of reported results. Future research priorities involve enhancing long-term reliability, energy efficiency, data security, and system-level integration through coordinated optimization across materials, devices, algorithms, and clinical evaluation strategies. In parallel, standardized assessment frameworks and comprehensive clinical validation are critical for facilitating the translation of embedded medical technologies into safe, reliable, and clinically applicable healthcare solutions.

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