



Smart implants with embedded biosensors for early detection of peri-implantitis

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ABSTRACT

Smart implants with embedded biosensors represent an emerging approach to improving the early detection and management of peri-implantitis. Conventional diagnostic methods primarily depend on clinical examination, probing, radiographic assessment, and detection of established tissue changes, which may limit the identification of early biological disturbances. Smart implant technology integrates miniature biosensors capable of monitoring local physiological and biochemical parameters, including temperature, pH, inflammatory biomarkers, microbial activity, and mechanical loading. These sensors can provide continuous or periodic information regarding changes in the peri-implant environment, potentially allowing inflammatory and infectious processes to be recognized before substantial bone destruction occurs. Integration with wireless communication, digital dentistry, and Internet-of-Things platforms may facilitate remote data transmission and longitudinal monitoring of implant health. Furthermore, combining sensor-generated information with radiographic imaging and clinical parameters could support individualized risk assessment and preventive intervention. Despite these advantages, challenges remain regarding sensor miniaturization, biocompatibility, durability, calibration, power supply, data security, and long-term clinical reliability. Future developments may incorporate multimodal biosensing and artificial intelligence to transform smart implants into predictive diagnostic systems. Overall, embedded biosensors have significant potential to shift peri-implantitis management from reactive diagnosis toward proactive, personalized, and continuous implant monitoring.

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INTRODUCTION

Dental implants have become an important treatment option for replacing missing teeth, providing functional and esthetic rehabilitation. However, their long-term success may be compromised by biological complications, particularly peri-implant mucositis and peri-implantitis. Peri-implantitis is characterized by inflammation of the peri-implant tissues accompanied by progressive supporting bone loss, making early recognition essential for preventing irreversible tissue destruction. Conventional monitoring approaches, including

clinical probing, radiographic examination, and assessment of peri-implant signs and symptoms, are generally performed periodically and may identify disease only after clinically relevant changes have developed (Bornes et al., 2023).

Advances in three-dimensional imaging and cone-beam computed tomography (CBCT) have improved visualization of anatomical and pathological changes and can support more accurate diagnosis and treatment planning (Singh, 2018). Nevertheless, imaging remains largely episodic and may not provide continuous information about the biological

Table 1: Major Biosensing Technologies for Smart Dental Implants

<i>Biosensing technology</i>	<i>Target parameter</i>	<i>Potential application</i>
Temperature sensor	Local temperature	Early inflammation/infection detection
pH sensor	Peri-implant pH	Detection of environmental changes
Biomarker sensor	Cytokines/inflammatory mediators	Early inflammatory monitoring
Microbial sensor	Pathogens/metabolites	Biofilm-related disease detection
Strain sensor	Mechanical loading	Detection of abnormal implant loading
Wireless/IoT module	Sensor data	Remote and continuous monitoring

environment surrounding an implant. Consequently, there is increasing interest in developing smart implants capable of detecting subtle physiological changes at an early stage.

Embedded biosensors offer a promising solution by enabling monitoring of parameters associated with infection and inflammation. In particular, implantable temperature sensors have demonstrated potential for real-time detection of infectious changes around dental implants (Kim et al., 2020). Other sensing approaches may target pH, inflammatory biomarkers, microbial activity, or mechanical loading. The biological environment and fluid dynamics surrounding oral tissues are also relevant considerations when developing reliable monitoring systems (Singh, 2020).

The development of smart implants further depends on appropriate titanium surface engineering to maintain biocompatibility, durability, and functional performance (Losic, 2021). Integration with Internet-of-Things (IoT) technologies could facilitate wireless data transmission, remote monitoring, and longitudinal assessment of implant health (Balaji Ganesh & Sugumar, 2021). Thus, smart implants with embedded biosensors represent a potential transition from conventional, reactive monitoring toward earlier, continuous, and personalized detection of peri-implantitis.

Design and Biosensing Technologies

Smart dental implants are designed to integrate sensing, communication, and implant-support functions within a compact, biocompatible system capable of monitoring the peri-implant environment. Their primary objective is to identify biological or mechanical changes associated with peri-implant disease before extensive tissue destruction becomes clinically evident. Novel implant-monitoring strategies increasingly emphasize objective and continuous assessment of implant health (Bornes et al., 2023).

A key component is the embedded temperature sensor, which can detect localized temperature elevations associated with inflammatory or infectious processes. Kim et al. (2020) demonstrated the development of a dental implantable temperature sensor for real-time infectious disease monitoring, supporting the feasibility of temperature-based early warning systems. Additional biosensing approaches may target pH, inflammatory biomarkers, microbial metabolites, and mechanical strain, providing multidimensional information about peri-implant tissue conditions.

The implant surface is equally important because sensors must remain stable and biologically compatible within the oral environment. Titanium surface-engineering strategies can improve corrosion resistance, biological integration, and functional performance, providing opportunities for incorporating advanced sensing technologies without compromising implant stability (Losic, 2021). Furthermore, imaging technologies such as CBCT can complement biosensor outputs by providing three-dimensional information about surrounding bone and implant structures (Singh, 2018).

Wireless connectivity and Internet-of-Things (IoT) technologies can facilitate transmission of sensor-generated information to external devices for longitudinal monitoring and clinical decision-making (Balaji Ganesh & Sugumar, 2021). Principles of controlled fluid and biological-environment management may also inform sensor design and interpretation of peri-implant conditions (Singh, 2020).

CLINICAL APPLICATIONS AND DIAGNOSTIC WORKFLOW

Smart implants with embedded biosensors can transform peri-implantitis monitoring from periodic clinical assessment toward continuous or near-real-time biological surveillance. Their primary clinical application is the early identification of inflammatory and infectious changes before extensive peri-implant tissue destruction becomes clinically or radiographically apparent. Local temperature monitoring is particularly promising because inflammatory and infectious processes may produce measurable thermal changes around implant tissues. The development of implantable temperature sensors demonstrates the feasibility of real-time monitoring of infectious conditions in dental implants (Kim et al., 2020).

A smart-implant diagnostic workflow can begin with baseline measurements obtained after implant placement and restoration. Subsequent sensor readings can be compared with the patient’s established physiological baseline to identify abnormal changes in temperature, pH, inflammatory biomarkers, microbial metabolites, or mechanical loading. These data can be transmitted wirelessly to digital platforms, supporting longitudinal monitoring and remote clinical assessment (Balaji Ganesh & Sugumar, 2021). Novel monitoring strategies may improve the diagnosis, prognosis, and maintenance of dental implants by providing additional

Table 2: Proposed Diagnostic Workflow for Smart-Implant Monitoring

Stage	Clinical Application	Outcome
Baseline	Record initial sensor and clinical measurements	Patient-specific reference
Continuous monitoring	Detect temperature, pH, biomarkers, or microbial changes	Early warning
Data transmission	Wireless/IoT transfer of sensor data	Remote monitoring
Clinical verification	Probing and clinical examination	Confirm suspected changes
Imaging	CBCT or other digital imaging	Assess structural involvement
Intervention	Preventive or therapeutic management	Limit disease progression

biological information beyond conventional clinical parameters (Bornes et al., 2023).

When abnormal sensor patterns are detected, clinicians can perform targeted clinical examination and complementary imaging. Three-dimensional imaging and CBCT may provide valuable information regarding peri-implant bone changes and anatomical conditions that cannot be adequately assessed through conventional two-dimensional approaches (Singh, 2018). The diagnostic process should therefore integrate biosensor signals with probing findings, radiographic evidence, patient symptoms, and other clinical indicators.

Sensor reliability is also influenced by implant surface characteristics, making appropriate titanium surface engineering important for maintaining biocompatibility and long-term functionality (Losic, 2021). Concepts of controlled biological monitoring and fluid-related diagnostic assessment may further inform sensor-based approaches to implant disease management (Singh, 2020).

ADVANTAGES, CHALLENGES, AND FUTURE PERSPECTIVES

Advantages

Smart implants with embedded biosensors offer a promising approach for the early and continuous monitoring of peri-implant tissues. Real-time measurement of temperature and other biological parameters may identify inflammatory or infectious changes before substantial clinical or radiographic manifestations develop. Implantable temperature sensing has demonstrated potential for real-time detection of infection-associated changes around dental implants (Kim et al., 2020). Integration of sensor information with clinical examination and advanced imaging, including CBCT, could improve diagnostic accuracy and support comprehensive implant monitoring (Singh, 2018; Bornes et al., 2023). Furthermore, IoT connectivity can facilitate remote transmission of implant-health data, enabling more personalized and preventive follow-up (Balaji Ganesh & Sugumar, 2021).

Challenges

Despite these benefits, several challenges must be addressed. Embedded sensors require long-term biocompatibility, mechanical stability, accurate calibration, and resistance to corrosion and biofilm accumulation. Titanium surface modification may improve implant performance, but

maintaining favorable biological interactions while incorporating sensing technologies remains complex (Losic, 2021). Power supply, wireless communication, data security, sensor miniaturization, and interpretation of continuously generated data are additional concerns. Moreover, sensor measurements should complement rather than replace established clinical and radiographic assessment. Reliable diagnostic protocols and long-term clinical validation remain necessary (Bornes et al., 2023).

Future Perspectives

Future smart implants may incorporate multimodal sensors capable of simultaneously detecting temperature, pH, microbial activity, inflammatory biomarkers, and mechanical changes. Integration with IoT platforms and artificial intelligence could enable predictive risk assessment and individualized intervention (Balaji Ganesh & Sugumar, 2021). Improved control of the peri-implant environment and reliable biological monitoring may further enhance preventive strategies, drawing on principles of fluid and biological management described in endodontic care (Singh, 2020). Ultimately, smart implants could shift peri-implantitis management from periodic, reactive diagnosis toward continuous, proactive, and personalized monitoring (Bornes et al., 2023).

CONCLUSION

Smart implants with embedded biosensors represent a promising advancement in the early detection and monitoring of peri-implantitis. By continuously or periodically assessing biological and physiological parameters such as temperature, pH, inflammatory biomarkers, microbial activity, and mechanical conditions, these systems have the potential to identify pathological changes before extensive peri-implant tissue destruction occurs. The development of implantable temperature sensors demonstrates the feasibility of obtaining real-time information from the implant environment for detecting infectious processes (Kim et al., 2020).

Integration of biosensor technology with established diagnostic approaches can further strengthen peri-implant disease assessment. CBCT and other three-dimensional imaging techniques provide valuable information regarding anatomical and osseous changes and may complement sensor-derived biological data (Singh, 2018). Such multimodal monitoring is consistent with emerging strategies for

improving peri-implant disease diagnosis, prognosis, and long-term implant surveillance (Bornes et al., 2023).

The successful development of smart implants will also depend on appropriate titanium surface engineering to ensure biocompatibility, stability, and long-term functional performance (Losic, 2021). Furthermore, IoT-enabled dentistry offers opportunities for wireless data transmission, remote monitoring, and integration of implant-health information into digital clinical workflows (Balaji Ganesh & Sugumar, 2021). Lessons from biological control and fluid-management principles in endodontics may additionally contribute to the refinement of infection-monitoring strategies (Singh, 2020).

Overall, smart biosensor-enabled implants could shift peri-implantitis management from reactive diagnosis toward proactive, personalized, and data-driven monitoring. However, long-term clinical validation, sensor durability, biocompatibility, data reliability, power management, and cybersecurity must be addressed before routine clinical adoption.

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