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SMART DENTAL IMPLANT –A GAME CHANGER IN DENTISTRY

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Abstract

Smart dental implants (SDIs) are transforming the field of oral healthcare by integrating advanced materials, sensors, and energy harvesting technology. These innovative implants address key challenges like implant failure and peri-implantitis through antimicrobial materials, built-in phototherapy, and real-time health monitoring. By harnessing piezoelectric nanoparticles, SDIs generate electricity from natural oral motions such as chewing and brushing, eliminating the need for external power sources.This renewable energy powers LEDs for light therapy, which promotes healing and reduces inflammation. Additionally, embedded micro-sensors wirelessly transmit oral health data, allowing for early detection of potential issues. Recent research demonstrates the effectiveness of SDIs in reducing bacterial biofilm formation and enhancing implant durability, promising better outcomes for patients. As the global population ages and the demand for dental implants increases, SDIs represent a groundbreaking advancement with applications beyond dentistry, including joint replacements and other medical implants. While challenges remain in terms of cost, scalability, and biocompatibility, the future of SDIs is bright, offering a smarter, more sustainable approach to oral health.

Keywords: Piezoelectric nanoparticles, Photobiomodulation therapy, Micro-sensors.

Introduction

Dental implants are a widely used solution for tooth replacement, with millions of procedures performed globally each year.[1] Despite their success, traditional implants face significant challenges, including peri-implantitis, bacterial infections, and eventual failure.[2] After tooth extraction the remnants of the periodontal ligament break down and disappear; and with them the information on the force exerted when biting and chewing is lost, as well. This lack of information justifies the frequent failure and breakage of dental prostheses These issues not only impact patient outcomes but also increase healthcare costs and the need for revision surgeries.[3]

Accurate implant placement begins with precise diagnosis and planning. While panoramic and periapical images were once standard, CBCT scans have become essential. They provide 3D imaging, cross-sectional views, and digital DICOM data, which enable virtual planning, creation of surgical guides, and prosthesis fabrication before surgery.[4] The increasing adoption of dental implants for treating missing teeth is driven by advancements in implant dentistry and supported by growing research on implant design, materials, and clinical behavior. Although implant sales are rising worldwide, North America lags behind Europe, which led the global market in 2016.[5]

The development of Smart Dental Implants (SDIs) addresses these limitations by combining advanced materials, energy-harvesting technology, and embedded sensors to enhance functionality and longevity.[1] SDIs offer a revolutionary approach to oral healthcare, utilizing piezoelectric nanoparticles to generate electricity from natural oral motions. This renewable energy powers LEDs for phototherapy, which aids in healing and infection prevention.[2] Additionally, SDIs are equipped with micro-sensors that monitor oral health metrics such as pH, temperature, and bacterial presence. This data is transmitted wirelessly to healthcare providers, enabling proactive intervention.[25]

This article explores the components, applications, materials, challenges, and future perspectives of SDIs, highlighting their potential to redefine patient care.

Components

The Smart Dental Implant (SDI) system utilizes a screw-retained crown design, a widely accepted clinical standard. Its primary components include an implant abutment, a dental crown, integrated circuitry, micro LEDs, and a securing screw. A distinguishing feature of the SDI is its energy-harvesting dental crown, designed to convert natural oral motions, such as chewing and brushing, into electrical energy. This is achieved through a carefully engineered two-phase composite structure:

Piezoelectric Material

The crown incorporates barium titanate nanoparticles (BTNPs), a lead-free piezoelectric material ideal for biomedical use. These nanoparticles generate electrical energy in response to mechanical stress, which powers the implant's functions.

Two-Phase Composite Design

0–3 Composite: Features 0-dimensional BTNPs embedded in a 3-dimensional matrix, enhancing the interaction between piezoelectric particles and oral biomechanics for efficient energy harvesting.

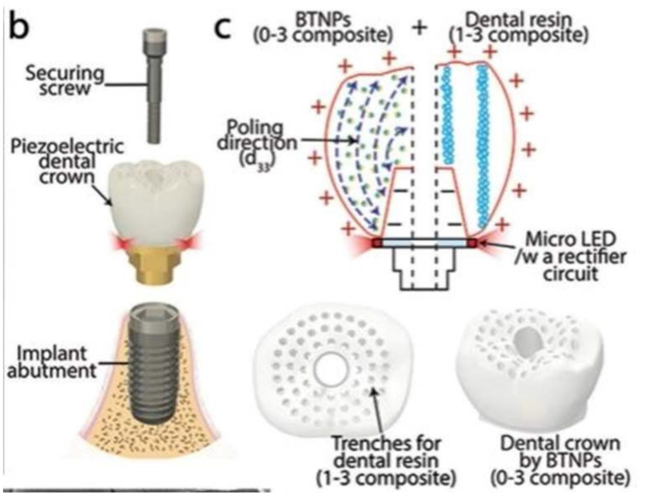

Fig.1 1–3 Composite

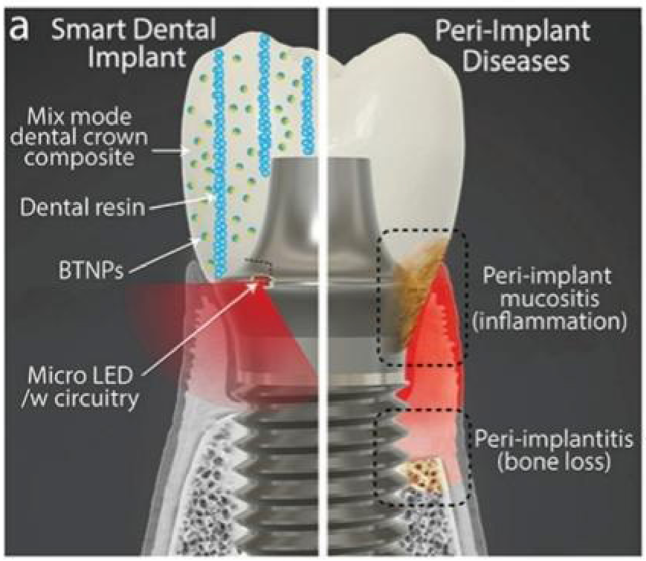

Fig. 2 A smart dental implant

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1–3 Composite: Combines 1-dimensional resin pillars with a 3-dimensional BTNP-based composite to provide the mechanical strength needed to endure the forces from chewing and brushing. (Fig.1)

Customized Fabrication

The piezoelectric crown is manufactured using paste extrusion 3D printing, a technique that allows for the production of patient-specific designs. This customization ensures the crown fits the patient's unique anatomy while maintaining optimal functionality.[1]

Our study demonstrated that the SDI system effectively harnesses human oral motion to generate sufficient energy for preventing peri-implant disease. However, the performance was tested under ideal conditions, such as continuous oral motion at optimal frequencies. To enhance functionality, a transistor switch could be incorporated into the circuitry to store harvested energy during oral motion and release it later when sufficient power is accumulated to operate the LEDs.

Long-term reliability will require improved packaging. While the current parylene coating provides adequate moisture and dielectric protection, more robust sealing is necessary to fully isolate embedded electronics from the oral environment. Embedding multiple LEDs at the base of the crown could enhance Photobiomodulation therapy by ensuring comprehensive coverage of surrounding gingival tissues, where peri-implant diseases typically develop. Finally, while the current SDI uses dental resin, which may not match the mechanical strength of commercially available dental crowns, exploring advanced materials like zirconia could significantly improve durability and structural integrity.[1] (Fig.2)

Integrated Sensors

Micro-sensors embedded in SDIs monitor vital

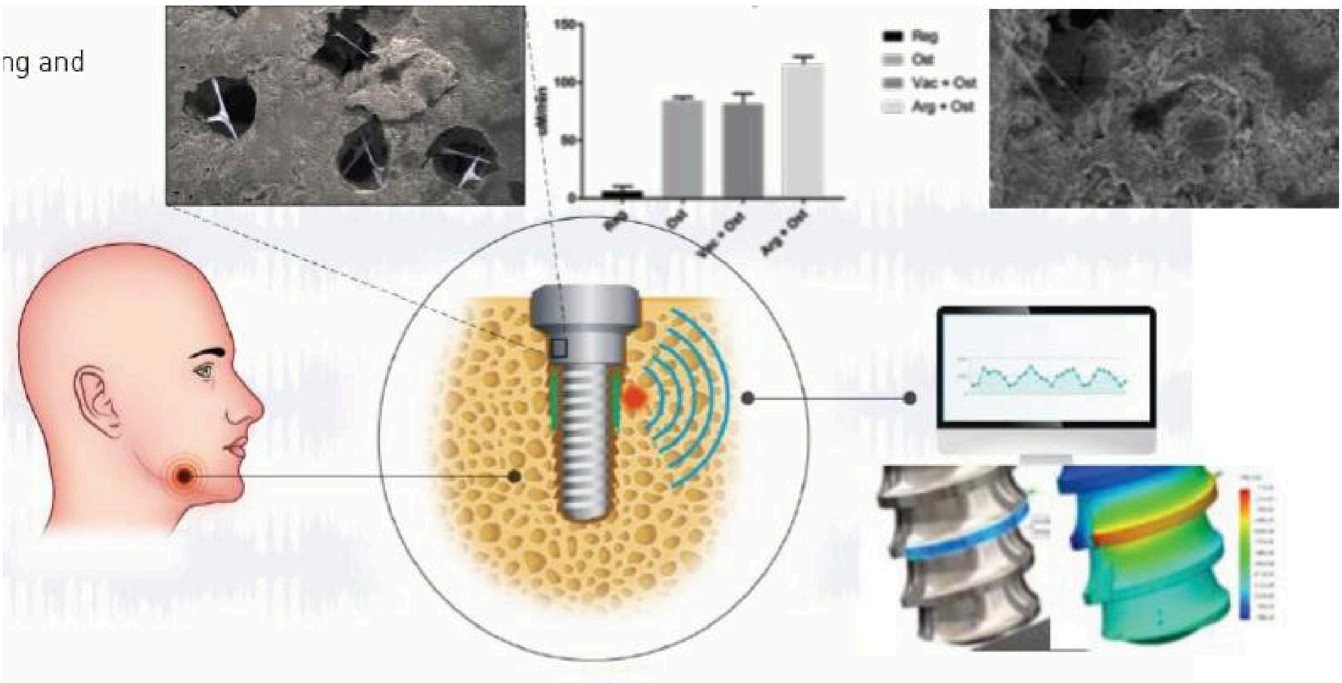

Fig. 3 Integrated Sensors in smart dental implant

oral health metrics, including pH, temperature, and bacterial presence. These sensors transmit data wirelessly to healthcare providers, enabling continuous monitoring and early intervention (Fig. 3).[24]

Applications

The primary application of SDIs is in oral healthcare, where they address challenges such as implant failure, infection, and inflammation. By providing real-time monitoring and built-in phototherapy, SDIs improve patient outcomes and reduce the risk of complications.[2]

Beyond dentistry, the principles of SDIs have broader applications in medicine. For example, the same energy-harvesting and sensor technologies could be applied to orthopedic implants, such as joint replacements, to monitor healing and detect early signs of failure. Additionally, antimicrobial materials used in SDIs could be adapted for use in other medical devices, reducing infection risks and improving patient safety.

Materials and Techniques

The materials and techniques behind smart dental implants (SDIs) embody a revolutionary integration of energy harvesting, photobiomodulation therapy (PBMT), antimicrobial defense, and real-time health monitoring. These features address critical challenges such as bacterial infections, inflammation, and implant longevity. Central to this innovation are advanced sensors, piezoelectric materials, and a seamless integration of therapeutic technologies.

Energy Harvesting through Oral Motions

A cornerstone of SDI technology is its ability to convert mechanical energy generated by natural oral activities chewing and brushing into electrical energy. This is achieved through the integration of piezoelectric nanoparticles, such as barium titanate nanoparticles (BTNPs). These nanoparticles produce electrical charges when subjected to mechanical stress, providing a sustainable and self-sufficient energy source for the implant.

Chewing Dynamics: Forces up to 200 N and frequencies of 1–5 Hz generated during chewing are converted into electrical energy.

Brushing Movements: The shear forces (15–70 N) and normal forces (12 N) associated with brushing are harnessed to sustain implant operations.

Energy Output: The harvested energy powers critical implant functions, with light energy densities reaching 0.77 μJ cm^2 s^{-1} at 5 Hz, equating to 4.1 mJ cm^{-2} over 90 minutes of oral activity.

This self-sustaining energy mechanism ensures that the implant remains operational without external power sources, eliminating the need for battery replacements or recharging.[1]

Photobiomodulation Therapy (PBMT)

Powered by the harvested energy, PBMT is a key feature of SDIs, utilizing embedded LED systems to emit therapeutic wavelengths of light. Blue light therapy is a clinically accepted approach to kill a pathogen, such as Propionibacterium acnes infections. This therapy offers multifaceted benefits:

Bacterial Defense: The emitted light disrupts bacterial biofilm formation, reducing the risk of infections and implant failure.

Inflammation Reduction: PBMT mitigates inflammation by modulating cellular activity in the gum tissue, promoting faster healing and reducing discomfort.

Tissue Regeneration: By stimulating collagen production and cell proliferation, PBMT supports the regeneration of gum tissue and enhances tissue integration with the implant.

The LEDs are strategically positioned within the implant to ensure even distribution of therapeutic light across the surrounding tissue, maximizing the benefits of PBMT during routine oral activities.[1]

Integrated Sensors for Real-Time Monitoring

A hallmark feature of SDIs is their embedded micro-sensors, which continuously monitor the implant's surrounding environment. These sensors are powered by the energy harvested from oral motions and provide critical insights into oral health parameters, including:

pH Levels: Variations in pH can indicate bacterial activity or the onset of infections.

Temperature: Monitoring temperature fluctuations helps detect inflammatory responses or potential complications.

Bacterial Activity: Real-time data on bacterial colonization around the implant site enables early intervention.[24]

The data collected by these sensors is wirelessly transmitted to external devices such as smartphones, tablets, or dental office systems. This enables real-time monitoring by dental professionals, allowing them to predict potential failures, address issues early, and optimize patient outcomes.[25]

Antimicrobial Coatings and Surface Design

To further enhance infection prevention, SDIs incorporate antimicrobial coatings using BTNPs. These coatings create a hostile environment for bacterial adhesion and biofilm formation, reinforcing the implant's defenses.

Modeling and Simulating Oral Motions

To optimize the implant's energy-harvesting capabilities and durability, researchers utilize advanced simulation techniques:

Chewing Machines: Electromechanical universal test machines simulate chewing forces and frequencies, ensuring the implant's performance under real-life conditions.

Brushing Apparatus: Custom rotational devices replicate brushing movements, testing the implant's resilience and energy efficiency.[1]

Mechanical and Biomechanical Testing

Mechanical testing ensures the structural integrity of SDIs. Flexural strength and modulus are assessed using three-point bending tests on composite materials infused with BTNPs. These evaluations confirm the implant's capacity to endure the mechanical stresses of daily oral activities.[1]

Biocompatibility and Cellular Studies

Biocompatibility is a critical factor for SDIs. Cellular studies with human gingival keratinocytes (HGKs) validate the safety and efficacy of PBMT and antimicrobial coatings. When exposed to bacterial lipopolysaccharides (LPS), cells treated with PBMT show reduced inflammation and improved viability, demonstrating the therapy's protective and regenerative properties.

Synergy Between Sensors and PBMT

The integration of sensors and PBMT creates a synergistic approach to oral health management. Sensors detect early signs of bacterial growth or inflammation, while PBMT actively mitigates these issues. This dual mechanism ensures a proactive and comprehensive defense against complications.

Innovative Material Science and Future Enhancements

Emerging designs for SDIs include asymmetric surfaces, with one side optimized for tissue integration and the other for bacterial resistance. This approach balances healing and infection prevention, enhancing the implant's overall performance.

Discussion

Tooth loss is a significant life event that affects two essential functions—eating and speaking—and has considerable impacts on various aspects of quality of life.6 Patients fitted with conventional removable dentures reported low satisfaction and only modest improvements in quality of life compared to those rehabilitated with implants.[7] The outcome of oral treatment with conventional dentures, whether successful or not, depends on various factors, including the practitioner's technical expertise and challenging oral conditions.[8]

Research highlights the critical role of bone volume in planning oral implants, recommending a minimum of 10 mm in height and 6 mm in width for the maxilla, and 6 mm in height and 5 mm in width for the mandible, to ensure successful implantation.[9] Periodontitis and cigarette smoking are linked to a higher risk of implant failure, as they reduce the vascularity of local tissues and disrupt healing, chemotaxis, and systemic immunity.[10]

The distinction between a failed implant and a failing implant is clinically significant. A failed implant is typically identified by a lack of osseointegration, characterized by implant mobility and peri-fixtural radiolucency. In contrast, a failing implant refers to a gradual and ongoing process, marked by progressive marginal bone loss without significant mobility.[11] Prospective and retrospective studies report success rates ranging from 84.9% to 100% in longitudinal studies spanning up to 24 years. However, failures, though infrequent, often occur unexpectedly. In addition to implant loss, early marginal bone loss around endosseous implants is also considered a sign of failure. Implant loss is categorized as either early failure, occurring before osseointegration, or late failure, occurring after the implant is subjected to occlusal load.[12] Currently, partially edentulous individuals constitute the largest and growing group of patients seeking rehabilitation with oral implants. Most of these patients are middle-aged, typically between 40 and 50 years old, when they receive implants. Given the increasing life expectancy, it is likely that these patients will require their implant-supported restorations to function effectively for several decades.[13] In fixed implant-supported dentistry, biological and technical complications are common. These issues can negatively affect the functionality and aesthetics of the prosthesis, even with high clinical expertise and proper prosthetic design.[14]

Peri-implant diseases are classified as either peri-implant mucositis or peri-implantitis, both of which are considered infectious conditions. Peri-implant mucositis is characterized by soft tissue inflammation around a functioning dental implant, along with bleeding on probing (BOP). In contrast, peri-implantitis involves the loss of supporting marginal bone beyond normal bone remodeling. While peri-implant mucositis is believed to be reversible, peri-implantitis is more challenging to reverse.[15] At the 1st European Workshop on Periodontology in 1993, peri-implantitis was defined as an inflammatory reaction accompanied by the loss of supporting bone in the tissues surrounding a functioning implant (Albrektsson & Isidor, 1994). However, this definition lacked specific clinical and radiological criteria for inflammation and bone loss, which hindered detailed analysis of the various risk factors contributing to peri-implantitis.16The need to assess the prevalence of peri-implant diseases at the subject level was emphasized, highlighting that the prevalence of mucositis is approximately 80% at the subject level and around 50% at the implant level. Peri-implantitis was found to occur in 28% to over 56% of subjects and in 12% to 43% of implants in the study.[17]

The transition from peri-implant mucositis to peri-implantitis marks the onset of peri-implantitis. However, assessing this shift is challenging, as it requires identifying early signs of supporting bone loss. Additionally, documenting the onset of the disease from a research perspective necessitates a longitudinal approach. While a prospective study may not be ethically feasible, a retrospective evaluation of peri-implant bone loss in radiographs of patients with advanced peri-implantitis is justifiable. In addition to determining the onset of peri-implantitis, radiographs can also be used to assess the disease's progression.[18]

Peri-implantitis was defined by the presence of plaque, suppuration, bleeding on probing (BOP), and probing depth (PD) greater than 5 mm. The analysis of peri-implant sulcular fluid was also used as a diagnostic aid, though no specific marker for peri-implantitis was identified. Variations of these diagnostic criteria for peri-implant diseases are also found in the literature. For instance, peri-implant mucositis was diagnosed based on BOP/suppuration and a PD greater than 4 mm, while peri-implantitis required a PD greater than 5 mm, along with radiographic bone loss of more than 0.2 mm annually or progressive bone loss exceeding 3 threads, combined with signs of peri-implant mucositis.[19] The peri-implant mucosal connective tissue attachment shares some clinical and histological similarities with that of natural teeth. However, the key difference lies in the cellular composition and fiber orientation. The connective tissue around a dental Implant is in direct contact with the titanium dioxide surface and contains a dense network of collagen fibers. These fibers, arranged in major bundles, originate from the periosteum of the alveolar bone crest and extend to the mucosal margin, running parallel to the implant/abutment surface. In contrast, the connective tissue attachment teeth involves collagen fibers that insert perpendicularly into the root cementum.[20]

The difference in the orientation of gingival fibers around implants, compared to natural teeth, is a key finding related to peri-implant mucosa. This variation allows bacteria to more easily penetrate the epithelial layer and reach the connective tissue, contributing to increased breakdown of soft tissues around implants.[21]

Bacterial infections are the primary cause of dental implant failure. The bacterial flora associated with periodontitis and peri-implantitis are found to be similar. The microorganisms most commonly linked to implant failure include Gram-negative anaerobes such as Prevotella intermedia, Porphyromonas gingivalis, Aggregatibacter actinomycetemcomitans, Bacteroides forsythus, Treponema denticola, Prevotella nigrescens, Peptostreptococcus micros, and Fusobacterium nucleatum.[22]

Cell-to-cell contact in a physiological context can occur between the same type of cells or between different cell types, such as keratinocytes and fibroblasts, which form the soft tissue seal around dental implants.[23]

Photobiomodulation (PBM) therapy, also called low-level light therapy (LLLT), has gained attention for its significant biological benefits. It effectively promotes tissue healing, reduces inflammation, and mitigates bacterial activity, making it a promising approach in addressing peri-implant complications. Our SDI system is an enhanced version of traditional dental implants, featuring energy harvesting and light delivery through a piezoelectric dental crown and integrated LEDs. Mechanical actions such as chewing and brushing generate electrical energy, which is stored in a capacitor and then used to power the LEDs.[1]

Challenges

While SDIs offer numerous benefits, they also face significant challenges. These include the high cost of materials and manufacturing, ensuring long-term biocompatibility, and navigating complex regulatory pathways for approval. Additionally, integrating multiple technologies into a single implant requires precise engineering and robust testing to ensure reliability.

Future Perspectives

As research progresses, SDIs are expected to become more cost-effective and widely available. Advances in materials science and manufacturing techniques will further enhance their functionality and durability. Moreover, the principles of SDIs could be extended to other medical applications, revolutionizing healthcare across multiple fields.

Conclusion

Smart dental implants represent a groundbreaking advancement in oral healthcare, addressing key challenges like infection, inflammation, and implant failure. By integrating energy-harvesting nanoparticles, antimicrobial materials, and real-time monitoring capabilities, SDIs offer a smarter, more sustainable solution. While challenges remain, the future of SDIs is promising, with the potential to transform implant technology and improve patient outcomes worldwide.

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