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Potential Use of SMART Implants in Traumatology and Orthopedics: A Review

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ABSTRACT

This review presents current scientific data on the use of biosensors in traumatology and orthopedics. Biosensors are specialized devices that detect various physicochemical parameters in the body. These parameters can be used to monitor, predict, and manage a variety of processes in orthopedic and trauma care. Technological advances enable the integration of biosensors and the development of customized implants. Their introduction has marked a significant breakthrough in trauma and orthopedic surgery, particularly with the emergence of SMART (Self-Monitoring Analysis and Reporting Technology) implants, which integrate microchips, wireless connectivity, and data analysis algorithms.

With the expected increase in surgeries and the growing need for implants, technological progress in this field is bound to continue and accelerate. Existing issues such as implant instability, infectious complications, and nonunions further underscore the relevance of this topic and the need for further research.

This analytical review was conducted using medical scientific databases and search engines, including PubMed (MEDLINE), Google Scholar, and eLibrary. The review addresses the following aspects: relevance, types of biosensors, their clinical applications, and prospects in traumatology and orthopedics. The review aims to improve understanding of biosensor uses in this medical field.

Keywords: SMART implants; biosensors; traumatology and orthopedics.

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Перспективы применения «умных» имплантатов в травматологии и ортопедии. Обзор литературы

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АННОТАЦИЯ

Представлен обзор литературы, посвящённой применению биосенсоров в травматологии и ортопедии. Биосенсоры — это специализированные устройства, которые могут воспринимать различные физико-химические показатели в организме. Данные показатели могут быть использованы для контроля, прогнозирования и управления различными процессами в травматологии и ортопедии. Развитие технологий позволяет интегрировать биосенсоры и создавать персонализированные имплантаты. В травматологии и ортопедии их внедрение стало прорывом, особенно с появлением SMART-имплантатов (Self-Monitoring Analysis and Reporting Technology), которые сочетают микрочипы, беспроводную связь и алгоритмы анализа данных.

В связи с прогнозируемым увеличением оперативных вмешательств и ростом потребности в имплантатах развитие технологий в данной области, несомненно, будет продолжаться и набирать обороты. Существующие проблемы в виде нестабильности имплантатов, инфекционных осложнений и несращений также делают данный вопрос актуальным и требуют дальнейших исследований.

Обзор носит аналитический характер и проведён с использованием баз данных медицинской литературы и поисковых ресурсов PubMed (MEDLINE), Google Scholar и eLibrary. В обзоре затронуты следующие аспекты: актуальность, виды биосенсоров, область их применения и перспективы в травматологии и ортопедии. Целью обзора является углубление знаний о применении биосенсоров в травматологии и ортопедии.

Ключевые слова: «умные» имплантаты; биосенсоры; травматология и ортопедия.

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BACKGROUND

Advances in treatment technologies and the accumulation of long-term outcome data identify the challenges that we will face and need to address in the near future. These include instability of metal constructs, implant-associated infections, the need for rehabilitation monitoring, and issues of consolidation and osseointegration. Understanding these challenges necessitates the formalization of tasks, the solutions of which require expertise beyond that of traumatologists and orthopedists alone. The success of implementation will depend on the interdisciplinary work of a team that, under current conditions, should include traumatologists and orthopedists, engineers, biotechnologists, materials scientists, specialists in artificial intelligence and nanotechnology, cybersecurity experts, chemists, physicists, microbiologists, and others. Paradoxically, the relevance of this issue in Russia is also linked to the fact that patients live in various cities, including remote areas, which significantly complicates implant status monitoring. Currently, there is a tendency toward shorter inpatient stays due to a combination of factors. Patients typically remain in the hospital for about 5–6 days before returning home, which further supports the rationale for using biosensors for continuous remote monitoring. Although this field is still at an early stage of development, the prospects for creating SMART implants appear highly promising. An interdisciplinary approach will enable more effective integration of these devices, opening new avenues for clinical application in the future.

SEARCH METHODOLOGY

The sources of information were full-text publications in foreign and Russian journals, selected from the PubMed (MEDLINE), Google Scholar, and eLibrary databases using the following key terms: sensor technology, Smart Sensor, artificial intelligence, intelligent implant, machine learning, orthopedics, and trauma, as well as from the Scientific Electronic Library eLIBRARY (eLibrary.Ru) using the key terms биосенсоры в травматологии и ортопедии (biosensors in traumatology and orthopedics) and умные имплантаты (SMART implants).

DISCUSSION

Prospects for Biosensors in the Prevention of Implant-Associated Infections

Infectious complications related to implants represent a serious clinical challenge. In the Russian Federation, the assessment of the prevalence of implant-associated infections is hindered by the absence of relevant data in federal statistical reporting forms. Information on surgical site infections (SSIs) is presented in the official reports of Rospotrebnadzor (Section 1.3.3. Healthcare-Associated Infections) without specifying their association with implanted

devices. For example, the 2022 report indicates that, in 2015–2019 (before the SARS-CoV-2 pandemic), the proportion of SSIs among all healthcare-associated infections averaged 23.17%. The main difficulty in this area lies in the formation of bacterial biofilms on implants, which significantly complicates infection management. Without timely eradication of bacteria at an early stage, implant removal becomes inevitable. Therefore, early diagnosis of infection is crucial for timely treatment and the prevention of subsequent complications.

Beyond the economic costs associated with prolonged therapy and repeated surgical interventions, this problem can lead to severe outcomes, including death. Evidence suggests that the five-year survival rate for periprosthetic joint infection is worse than that for four out of the five most common cancers [1, 2]. Considering these data, the development of early diagnostic approaches is of paramount importance for reducing the risk of infectious complications at surgical sites.

A promising avenue in this field is the creation of SMART implants with integrated biosensors capable of detecting the onset of infection process before clinical signs appear. Such biosensor-enabled implants can complement orthopedic devices to predict and diagnose infectious complications at an early stage, personalize treatment, and reduce the risk of complications.

Local temperature elevation or changes in the pH of the environment may be the first signs of a developing inflammatory process. Several types of biosensors have been designed for the early diagnosis of infectious complications:

- Thermosensitive implants, or temperature sensors. Their operating principle is based on an inductive-capacitive resonance circuit. They are inductively activated, allowing non-contact temperature measurement. This sensor provides temperature readings in the range of 30–42 °C, ensuring high reproducibility of results and temperature control around implants [3]. Undoubtedly, inflammation at the site of an infectious process is accompanied by elevated temperature; however, in the case of a slow-progressing process and low-grade chronic infection, this indicator may be uninformative [4].
- Lactate sensors. Changes in lactate levels can be an indicator of metabolic alterations associated with infection. Studies have demonstrated highly sensitive biosensors capable of continuous real-time lactate monitoring, enabling rapid identification of inflammatory processes [1]. The device is based on the enzyme lactate oxidase immobilized on an electrode. These biosensors determine lactate concentration—a marker of hypoxia and bacterial activity. Normal values are 0.5–2.2 mmol/L; in infection, levels exceed 4 mmol/L. The operating mechanism is as follows: lactate oxidation generates an electrochemical signal proportional to its concentration.
- pH sensors. Ion-selective electrodes with membranes sensitive to hydrogen ions measure the acidity of the

medium (normal tissue pH is 7.35–7.45; in infection, it decreases to 6.5–7.0). Changes in pH cause a shift in the electrode potential, which is recorded by a transducer [5].

- Lactate and pH sensors. These sensors are a combined system capable of continuously determining both parameters in real time, which can not only serve as an inflammation marker but also improve the management of critically ill patients by enabling correction of these parameters [5].
- Sensors for protein markers of inflammation (such as interleukin-6 and tumor necrosis factor) can also continuously determine protein concentrations, with a rapid response allowing real-time detection of changes in marker levels [6].

The installation of these biosensors, despite their small volume ($<0.25\text{ cm}^3$), should be carried out in areas that are not subject to mechanical load and in regions with low stress, so as not to affect the biomechanics of the implant itself [7].

In addition, there are biosensors for the detection of various proteins and DNA [8], and biosensors based on immunological reactions, such as the antigen–antibody interaction, are also widely used [9].

Single-marker sensors have low specificity, which complicates the differentiation of the infectious process. In this regard, a promising direction is the development of sensors capable of simultaneously detecting several specific biomarkers associated with bacterial infection (for example, inflammatory markers, products of bacterial metabolism). Given the significant social and economic impact of implant-associated infections, the creation of such universal systems for early infection prediction is of particular importance.

Significant progress has been made to date in the development of biosensors with high specificity that can operate in liquid media, including biological fluids [10]. The specificity of detecting a wide range of biological markers in such sensors is achieved through the use of recognition elements, which may include enzymes [11], antibodies [12], aptamers [13–15], or whole cells [16]. In addition to their high specificity, the main advantages of biosensors with recognition elements are their very broad spectrum of detectable markers and ultra-high sensitivity, down to 1 molecule per μL [17]. The main drawbacks of biosensors are associated with the fact that many recognition elements do not possess high stability under normal environmental conditions. Moreover, the architecture of biosensors often requires the use of fluorescent labels [18, 19] for detecting the sensor response, which limits their placement inside a living organism and, accordingly, their integration into implants.

A promising solution to this problem may involve various electrochemical sensors with an electrical response [20], such as resistive, capacitive, or various types of transistor-based sensors containing aptamers as recognition elements. The use of electrical characteristics for detecting the sensor response eliminates the need for fluorescent labels [21]

and significantly simplifies the measurement of the sensor output, including in flow-through mode [22]. This enables the placement of electrochemical sensors inside a living organism, which is impossible for mass-sensitive biosensors and extremely challenging for optical ones.

In addition, the electrochemical method of analyte detection offers advantages associated with a wide range of possible response parameters, such as voltage, current, capacitance, total output power, or electrochemical impedance, as well as low theoretical detection limits resulting from differences between Faradaic and non-Faradaic currents.

The use of aptamers as recognition elements makes it possible to select almost any inflammation marker specific to a given process as the target analyte, including cytokines, C-reactive protein, and TNF- α [23]. Furthermore, the possibility of creating a multisensor chip—a so-called “lab-on-a-chip” [24]—capable of simultaneously responding to pH and a selected specific analyte should enable not only the detection of an inflammatory process within a living organism, but also the identification of processes localized specifically at the site of implant placement.

International publications describe numerous biosensors based on electrochemical sensors—particularly field-effect transistors with various recognition elements, including aptamers, for the detection of a wide range of biochemical markers, such as alpha-fetoprotein [25], dopamine [26], cortisol [26], prolactin [12], alpha-synuclein [16], and many others. It should be noted that the functionality of all the above-mentioned biosensors has so far been demonstrated only *in vitro*, in model media or real biological fluid samples such as saliva, blood, and urine. Therefore, further efforts are required to develop biosensors of this type that can operate inside a living organism.

Among the described developments, including all types of sensors, a substantial proportion operates in the format of devices with biosensors implanted subcutaneously, with the contact surface exposed to the skin [6, 27, 28], or requiring implantation directly under the skin for measurement readout [29]. The following section will examine fully implantable sensors, without limitations on implantation depth, based on the requirements of traumatology and orthopedics.

Prospects for the use of biosensors in various areas of traumatology and orthopedics

A second important area in traumatology and orthopedics is the monitoring of bone consolidation and osseointegration, which can support early rehabilitation and mobilization of patients through the use of personalized data. The success of most orthopedic surgeries depends on the healing of soft tissues and bones, as well as the osseointegration of implants. Complications arising from these processes represent the main challenges in surgical treatment.

The absence of implant osseointegration, for example in the case of prostheses in bone, leads to implant instability and the need for repeat surgical interventions, as well as an

increased risk of infectious complications. Another component relevant specifically to traumatology is the consolidation of fracture fragments. In cases of impaired bone healing, the main load is borne by orthopedic implants, which leads to their damage or instability. This, in turn, results in repeat surgical interventions, which are generally associated with greater complexity and less favorable prospects for success compared with primary surgeries.

Despite advances in traumatology and orthopedics, surgical treatment methods, and the principles of osteosynthesis, these problems remain relevant to this day [30]. In this regard, the development of technologies enabling the monitoring of bone healing and osseointegration will allow the personalization of medical care for each patient and significantly reduce the risk of complications.

This field includes load and micromobility sensors, accelerometers, gyroscopes, and others [31].

Management of osseointegration and consolidation

At first glance, the assessment of fracture consolidation on radiographs may seem straightforward; however, studies have shown that it is a rather complex problem [32]. Moreover, research has demonstrated that correlating radiographic findings with mechanical stability is challenging. Clinicians were unable to determine the degree of fracture consolidation from a set of radiographic images or to rank the radiographs according to stability [33, 34]. The incidence of nonunion in fractures averages approximately 2% but, in some situations, may reach up to 20% [30, 35]. Determining bone union by measuring mechanical loads on the implant using sensors may serve as an objective method for assessing consolidation. Current studies demonstrate the potential of such biosensors in managing osteosynthesis and personalizing treatment [36, 37]. For example, in the study by Kienast et al. (2016), patients with femoral fractures were implanted with a biosensor attached to the fixation plate, which recorded real-time data on mechanical loads and micromobility [38]. Micromobility sensors enabled physicians to more accurately evaluate the processes of osseointegration and bone union. The data obtained from the sensors assisted in the early detection of possible complications, such as nonunion, which manifested as an increase in micromobility. Real-time micromobility monitoring allowed physicians to adapt treatment more effectively for each patient.

Experimental studies have confirmed the high accuracy of biosensors in monitoring mechanical parameters. For instance, the study by McGilvray et al. (2015) demonstrated that implantable micromechanical sensors provide detailed information on the healing process, including load distribution and microstrain within the callus [39]. These data are critical for predicting consolidation and optimizing rehabilitation timelines [39].

In addition to the above, there are studies in which self-powered sensors are used to monitor bone union process.

These sensors are powered directly by oscillations generated by deformation of the fixation device and, therefore, operate continuously. The output data from the sensors are curves that can be used to determine the processes of bone tissue healing [40].

The use of biosensors in external fixation is also noteworthy. In the study by Iyengar et al. (2022), the integration of sensors into Ilizarov-type and hexapod systems was discussed [36]. Sensors embedded in circular fixators were employed to monitor distraction osteogenesis, deformation of bone fragments, callus quality, and the accuracy of angular corrections. Such technologies provide continuous and objective healing control, which is not achievable with conventional radiographic methods.

The development of SMART implants for detecting micromobility is a promising direction in managing fracture consolidation. These microsensors allow for the personalization of orthopedic regimens and the early detection of nonunion, thereby increasing the success rate of surgical treatment. Furthermore, instability and an inflammatory microenvironment contribute to the development of implant-associated infections, which can also be prevented through the use of biosensors [41].

Application and potential in joint arthroplasty

At present, the implementation of SMART implants in joint arthroplasty already has a certain foundation [42]. In 2021, Zimmer Biomet introduced the innovative Persona IQ knee prosthesis equipped with multifunctional biosensors and a telemetry system [43]. The device includes an elongated tibial component with integrated sensors: a three-axis accelerometer, a gyroscope, and a wireless data transmission system [44]. These sensors enable monitoring of biomechanical parameters such as step count, walking speed, stride length, distance walked, and the angular range of tibial motion. The accelerometer records linear accelerations, whereas the gyroscope measures angular velocities, allowing highly accurate reconstruction of the joint's three-dimensional kinematics. The telemetry system, powered by a battery with a claimed lifespan of over 10 years, transmits data to external devices for analysis by physicians and patients. A key element of the system is the set of miniaturized biosensors adapted to operate under mechanical loads and within the biological environment. The sensors are made from biocompatible materials resistant to corrosion and deformation, which is critical for long-term implantation. Their integration into the 58-mm tibial component ensures measurement stability but poses engineering challenges due to the increased tibial component length. To minimize power consumption, an intermittent operating mode is used: in the first year, data are collected continuously (from day 2 to day 365); in the second year, data are collected for 36 days per quarter; and in subsequent years, for 36 days annually. Over a ten-year period, active battery use amounts to approximately

2 years and 2 months, reducing the risk of premature depletion [43].

The results of using this prosthesis help physicians understand how the prosthesis functions in real-world conditions and how it interacts with the patient's body. Sensor use allows the collection of objective data on joint movement and loading, which can be correlated with patients' subjective assessments. The study by Yocum et al. (2023) [42] demonstrates that patients may report high satisfaction levels, whereas objective indicators, such as range of motion and functional tests, may indicate insufficient recovery. This underscores the need for more accurate functional assessment methods [45].

Data obtained through sensors can be used for individualized prosthesis adjustment, potentially improving functional outcomes and patient satisfaction. For example, if the sensors indicate excessive pressure on specific areas, this may signal the need to modify the design or adjust the prosthesis. Integrating sensors into prostheses can not only improve understanding of the patient's current condition but also facilitate the development of more effective rehabilitation programs. Physicians will be able to monitor patient progress more accurately and adjust recovery protocols based on objective data.

In addition, there are studies aimed at the early prediction of endoprosthesis instability using specialized sensors [46]. Mohammadbagherpoor et al. (2020) presented an experimental model for the detection of early instability [47]. The system includes a sensor integrated into the prosthesis structure, which records implant displacement relative to the bone by measuring changes in the magnetic field. Data are transmitted wirelessly via inductive coupling, eliminating the need for built-in batteries and enhancing patient safety. The processing algorithms convert inductance fluctuations into quantitative parameters—linear displacement (with an accuracy of up to 10 μm) and angular deformation (with an

accuracy of 0.5°), which is critical for detecting early signs of instability [47]. A key advantage of the system is its ability to detect abnormal micromovements before the appearance of clinical symptoms or radiographic changes. For example, partial degradation of bone cement or the formation of fibrous tissue around the implant causes characteristic deviations in kinematics, which the system records and compares with predefined threshold values. This enables clinicians to predict the risk of prosthesis loosening at the preclinical stage and to adjust rehabilitation protocols—for example, by optimizing the load to extend the service life of the endoprosthesis.

There are also developments of endoprostheses equipped with thermistors for detecting temperature increases during movement, which may indicate increased friction. It is well known that after endoprosthesis implantation, a pseudosynovial membrane is formed, producing hyaluronic acid similar to natural synovial fluid. The properties of synovial fluid vary significantly with temperature, and at elevated temperatures it may lose its lubricating properties [48].

Under loading, the temperature in a joint with an endoprosthesis rises, which can affect the quality of the pseudosynovial fluid and, with prolonged exposure to high temperature, lead to aseptic necrosis. To assess the degree of temperature rise depending on friction pairs and types of endoprostheses, diagnostic methods were developed for detecting temperature increases during movement and for evaluating friction by integrating a thermistor into the neck of the implantable endoprosthesis (Fig. 1) [49].

The durability of biosensors can be enhanced by converting mechanical energy generated during knee movement into electrical energy. This allows powering the embedded sensors and other electronic components of the implant, making it more autonomous and functional. In the article by Ibrahim et al. (2019), both the technical aspects of implementing such systems and the potential benefits for patients are discussed, including improved health status

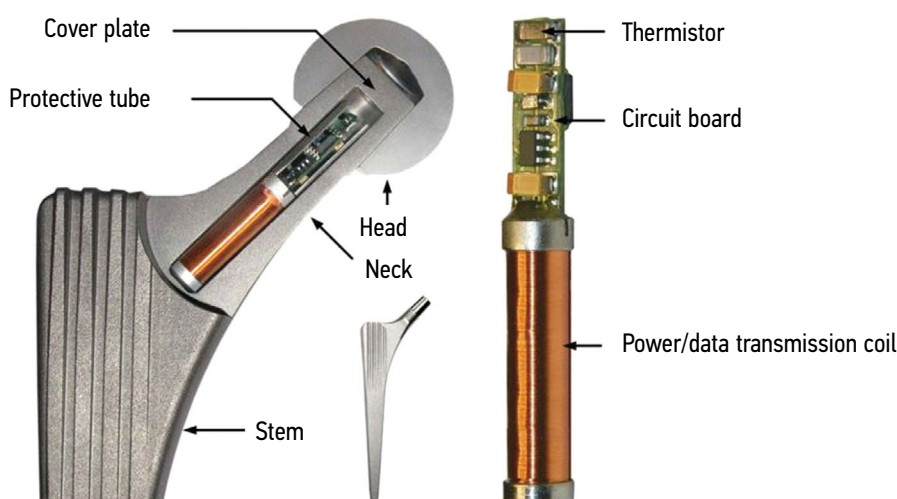


Fig. 1. Cross-sectional view of a modified hip joint endoprosthesis model. Temperature telemetry with thermistor, electronic circuitry and power/data coil are located inside the implant neck [49].

monitoring and the possibility of collecting physical activity data [50].

SMART implants in spine surgery

The first attempts to use strain gauges in spine surgery date back to 1966, when Harrington rods, used for scoliosis correction, were equipped with 10 strain gauges and implanted in three patients. These early SMART implants had lead wires exiting percutaneously to connect to external data recorders, enabling, for the first time, the assessment of mechanical loads on the construct *in vivo*. Despite limited accuracy and a high risk of infectious complications, this experiment laid the foundation for further research. A significant contribution to the development of the technology in the 1990s was made by the work of Rohmann, who proposed the concept of integrated strain gauge systems for continuous monitoring of spinal implants [51].

Modern strain gauges, e.g. by Szivek et al. (2022), are miniature devices mounted directly on metal constructs [52]. Their design includes fixation to rods and vertebral arches, providing feedback during the progression of spondylodesis. For example, strain gauges coated with calcium phosphate ceramics not only record the load but also enhance osseointegration, whereas uncoated devices demonstrate a higher risk of migration. A reduction in mechanical deformation of the implant by 15%–20% within three months serves as an objective marker of successful bone fusion, enabling adjustments in rehabilitation or planning of revision procedures [52].

Postoperative monitoring using biosensors offers opportunities for predicting complications such as pedicle screw instability and influencing spondylodesis processes. In clinical practice, this may be applied to prevent instability by modifying orthopedic regimens, as well as to provide information on the necessity of repeat or ventral surgical interventions. Furthermore, the technology allows for personalized rehabilitation by optimizing the timing of patient mobilization based on objective biomechanical data.

A promising area of research is the integration of Raman microspectroscopy into spinal implants and instruments. This technology, based on the analysis of molecular vibrations, enables real-time tissue identification with an accuracy exceeding 95%, thereby minimizing the risk of iatrogenic injury to neural structures. In addition, it can be adapted for integration into spinal implants and instruments, ensuring continuous monitoring of the condition of surrounding tissues [53].

Thus, the integration and application of biosensors in spine surgery hold considerable promise for personalizing and improving surgical outcomes.

Applications in soft tissues

Studies have been conducted on the development of biodegradable sensors designed to assess strain and pressure in soft tissues, particularly in tendons [54]. These sensors

can be implanted during surgical treatment and enable real-time monitoring of tissue extensibility. This, in turn, provides information on scar formation and tissue healing, thereby allowing for early rehabilitation. Standard rehabilitation protocols typically involve prolonged immobilization to protect the operated segment or area. However, such an approach increases the risk of adhesion formation and may lead to slower and more costly rehabilitation processes. The sensor proposed by Boutry et al. (2018) allows for the personalization of rehabilitation protocols based on extensibility data, reflecting the trends of the healing process [54].

Self-healing sensors

At present, nanohybrid systems can help to achieve a stable power supply for wireless systems and eliminate the need to replace or maintain batteries in medical implant sensors—particularly in humid environments. These systems are layered nanocomposites incorporating energy-storage components [57]. One of the promising approaches to addressing the challenge of developing an efficient and durable hybrid cell capable of withstanding cyclic mechanical loading and corrosive environmental effects is the use of self-healing materials that can restore their original structure and functions after damage [58]. Self-healing materials are artificially created substances or systems capable of partially or fully recovering their initial properties after sustaining damage.

Recent advances in self-healing materials for organic electronics have been successfully demonstrated in a wide range of emerging applications, such as SMART wearables and flexible devices [59]. A key requirement in designing self-healing conductors is maintaining high conductivity after damage and repair. A straightforward strategy for manufacturing self-healing conductors is to incorporate reversible bonds into conductive polymers. In lithium-ion batteries, the main goal is to increase capacity through the use of a self-healing polymer that binds the anode material together, enabling the production of a lithium-ion cell with a capacity of about 3000 mA·h g⁻¹ over 20 cycles. Reports have described the development of a durable polydopamine–graphene oxide–polyacrylamide (PDA–pGO–PAM) conductive hydrogel that mimics the adhesion mechanism of mussels while offering both self-healing and self-adhesive properties [60].

The use of self-healing sensors increases the service life of such devices [59].

One of the promising directions is the development of soft electronics devices based on metallopolymer with high mechanical properties, electrical conductivity, and biocompatibility due to reversible metal–ligand bonds [61]. In particular, such devices should withstand deformation and be able to self-heal in case of mechanical damage. An energy-storage triboelectric nanogenerator (TENG) has been developed, which can serve not only as a power source but also as a self-powered electronic skin [62].

It consists of a metal-coordinated polymer as a triboelectrically charged layer and an ion gel with hydrogen bonds as the electrode. Even after 500 cutting and healing cycles or under an extreme 900% strain, the TENG retains its functionality, i.e., intrinsic and autonomous self-healing capabilities under ambient conditions. In addition, it demonstrates high performance: fast healing time (30 min, 100% efficiency at 900% strain), high transparency (88.6%), and ultrastretchability (>900%).

Self-healing polymers are a promising way to address the problems of wear in polymer products under mechanical loads or environmental exposure [63]. Moreover, such supramolecular structures often exhibit stimulus-responsive properties—reacting to changes in temperature, pH, or humidity, which opens new prospects for the creation of SMART materials for medicine and electronics, sensors and actuators, as well as shape-memory materials.

Prospects for the application of bioluminescent biosensors in traumatology and orthopedics

Bioluminescent biosensors: a novel platform for monitoring

In the context of developing SMART implants, bioluminescent biosensors are of particular interest. These systems are based on enzymatic reactions, for example, using bacterial luciferase, and enable the detection of changes in the metabolic activity of surrounding tissues in real time [64].

Their key advantages include:

- High sensitivity: the ability to register minimal changes in metabolite concentration (e.g., lactate, NADH) or redox potential, which is relevant for early diagnosis of infections or hypoxia [65];
- Rapid analysis: the response time ranges from 5 to 30 minutes, which is critical for intraoperative or postoperative monitoring [66];
- Stability: immobilization of enzymes in gel matrices (e.g., starch or gelatin) increases the shelf life of reagents up to 2 years without loss of activity, facilitating their use in clinical practice [67];
- Versatility: the ability to adapt to various biomarkers (pH, lactate, redox status) through the combination of enzymes (e.g., NADH-oxidoreductase and luciferase) [68].

Applications in traumatology and orthopedics:

- Early detection of infections. Bioluminescent sensors can detect pH changes or lactate levels associated with bacterial activity, similar to the sensors described earlier in this review [5]. For example, a luciferase- [69] and NADH-oxidoreductase-based system can register redox changes characteristic of inflammation. Unlike thermosensors [3], such systems maintain sensitivity even in low-grade infections when temperature deviates only slightly from normal [4].

- Monitoring of osseointegration and consolidation. Enzymatic bioassays can be integrated into implants to assess osteoblast metabolic activity. A decrease in NADH levels (a marker of cellular respiration) may indicate impaired bone regeneration, correlating with micromotion data [38]. For instance, gel-immobilized multienzyme systems (e.g., Enzymolum) can perform multiparametric analysis, including redox status and medium acidity [70].
- Personalized rehabilitation. Portable bioluminescent luminometers (e.g., the Enzymolum laboratory system) can be used to analyze biological fluid samples (synovial fluid, blood) to assess the trends of soft tissue or tendon healing [54].

Technical aspects:

- Gel immobilization improves enzyme resistance to mechanical loads, relevant for implants under constant pressure [7].
- Microfluidic chips: miniaturization enables integration of sensors into prosthetic designs (e.g., into the neck of a femoral component [49]).
- Autonomy: combination with triboelectric generators can ensure energy-independent operation [50].

Examples of clinical implementation:

- Biosensors for toxicity monitoring are already in use for environmental control [71], but can be adapted to detect bacterial toxins in the periprosthetic area.
- Enzymatic bioassays are applied in the diagnosis of stress states via saliva [71], offering opportunities for noninvasive postoperative stress monitoring in orthopedic patients.

Bioluminescent biosensors developed by Kratasyuk and her colleagues from the Institute of Biophysics, Federal Research Center Krasnoyarsk Scientific Center of the Siberian Branch of the Russian Academy of Sciences, and the Federal State Autonomous Educational Institution of Higher Education Siberian Federal University (Krasnoyarsk) offer an innovative approach to creating SMART implants. Their key advantages—high sensitivity, rapid response, and capability for multiparametric analysis—make them promising for early infection diagnosis, osteointegration monitoring, and personalized rehabilitation. Further research should focus on integrating these technologies into existing implant systems and minimizing costs.

CONCLUSION

At present, the implementation of biosensors and SMART implants remains challenging due to their high cost and the lack of widespread practical application. This situation is similar to many other technologies that have gone through similar stages, such as mobile communications and computers. However, with the advancement of nanotechnology, microchips,

artificial intelligence, and the practical applicability of these technologies, they will undoubtedly hold considerable promise in the near future. Those who master these technologies at the early stage of their development may become leaders in this field. In turn, this will not only bring economic benefits to the Russian healthcare system but also enable competition in the global implant market.

Biosensors for the prevention of infectious complications will make it possible to detect them at early stages, thereby helping to prevent the formation of biofilms on implant surfaces. This could significantly reduce the economic costs associated with managing implant-associated infections. Most importantly, it would improve surgical outcomes, reduce the incidence of infectious complications, and enhance patients' quality of life.

In addition, these technologies may substantially reduce the number of complications related to implant instability and osseointegration. This could fundamentally change both the paradigm and frequency of such complications. Data obtained from microsensors could help to personalize orthopedic regimens according to the rate of bone fusion, which may not correspond to radiological findings and may manifest later, thereby limiting the patient's ability to resume full activity.

Furthermore, data on the trends of bone fusion will also enable physicians to perform revision surgeries earlier to achieve success. For example, the absence of any trend toward decreased micromotion over time may indicate a lack of callus formation. Gradual micromotion reduction, detected only by biosensor monitoring but not visible on radiographs, can help avoid unnecessary surgical interventions. Moreover, osseointegration rates vary significantly between individuals, yet recommendations for orthopedic regimen compliance are generally uniform. This may substantially limit the patient's activity and quality of life. Implants capable of reporting the status of fracture callus formation will promote earlier mobilization and serve as an additional factor in maintaining adherence to orthopedic regimens.

In addition, pressure and motion sensors can track postoperative rehabilitation processes and provide objective assessment using biosensor data. Such data can be used to personalize rehabilitation programs, adjust implant status, optimize orthopedic regimens, and carry out timely replacement of consumable components such as liners and other elements.

Pressure sensor readings may also reveal shortcomings in orthopedic devices and guide their modification toward creating optimal implants capable of evenly distributing loads. In device-assisted treatment, which is often quite complex, it is necessary to carry out lengthening procedures correctly, taking into account the varying potentials of each patient for regenerate formation. This process could also be automated based on biosensor data.

SMART implants in traumatology and orthopedics are transforming treatment approaches by integrating biocompatibility, digitalization, and personalization. Ultimately, the development of SMART implants and biosensors

embedded in bone structures may lead to the concept of a smart body, where individuals can assess the function of their own bodies and various systems based on sensor data. Inevitably, these technologies face—and will continue to face—challenges such as biocompatibility, biodegradability, longevity of operation, as well as numerous ethical issues related to data protection. However, given the current pace of technological development, their implementation appears likely in the near future.

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