

NEXT-GENERATION BIO-IMPLANTABLE ELECTRONIC SYSTEMS FOR MEDICAL DIAGNOSIS ENABLED BY ADVANCED MATERIALS

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Abstract

Recent advances in materials science and device engineering have enabled a new class of bio-implantable system with mechanical softness and biocompatibility that closely match living tissues. These soft electronic systems address long-standing limitations of conventional rigid implants, such as mechanical mismatch, chronic inflammation, and signal degradation, thereby expanding opportunities for long-term health monitoring and therapeutic intervention. This review summarizes recent progress in soft bio-implantable electronics with a focus on the clinical needs driving their development, the potential materials and structural designs enabling functional integration, and the mechanical properties that ensure stable operation in dynamic biological environments. We highlight material platforms that combine electrical performance with tissue-like mechanics, as well as design strategies that accommodate physiological motion while preserving device functionality. By bridging materials innovation with biomedical application, this review provides a comprehensive overview of the challenges and opportunities in translating soft implantable systems from laboratory research to clinical practice.

Keywords: Implantable, Diagnosis, Soft electronics, Mechanical design, Mechanical mismatch.

INTRODUCTION

The integration of electronic systems into the human body has fundamentally reshaped the future of modern medicine, enabling precise diagnostics, targeted therapies, and advanced rehabilitation strategies. Over the past few decades, implantable medical devices such as cardiac pacemakers (1), deep brain stimulators (2), spinal cord stimulators, and cochlear implants have demonstrated remarkable clinical impact, significantly improving patient survival rates and quality of life. Despite these successes, conventional implantable electronics are typically fabricated using rigid, brittle materials such as silicon, ceramic, and metal alloys with bulky design. While these materials provide excellent electrical performance and structural robustness, they exhibit mechanical properties that are orders of magnitude stiffer than soft biological tissues. Such mechanical mismatch can result in micromotion-induced tissue damage, chronic inflammation, fibrotic encapsulation, and progressive degradation of signal fidelity, especially for devices intended for long-term implantation. To address these challenges, a new paradigm in implantable device technology has emerged soft bio-implantable electronics in which the device's mechanical compliance and flexibility are engineered to match those of native tissues. By adopting materials and architectures that mimic the softness, stretchability, and conformability of skin, nerves, and other biological structures, these systems can intimately interface with the body without inducing significant mechanical irritation (3). Such tissue-conformal integration not only minimizes the body's foreign-body response but also enables stable, high-quality signal acquisition and reliable stimulation over extended periods. The development of soft implantable electronics has been driven by significant progress in advanced materials. Conductive polymers, liquid metals,

hydrogels, elastomers, and soft nanocomposites have emerged as key building blocks, offering a balance between electrical functionality and mechanical compatibility. These materials can be combined with structural engineering approaches such as serpentine interconnects, mesh layouts, and ultrathin structure to achieve high stretchability and fatigue resistance under physiological motion (Figure 1). Additionally, advances in thin-film encapsulation and biocompatible coatings have improved device longevity in the chemically complex, aqueous environment of the human body. Clinically, the demand for such devices spans a broad spectrum of applications. For instance, in bioelectronic medicine, fully implantable systems capable of closed-loop sensing and stimulation have the potential to modulate physiological processes such as inflammation, metabolism, and organ function.

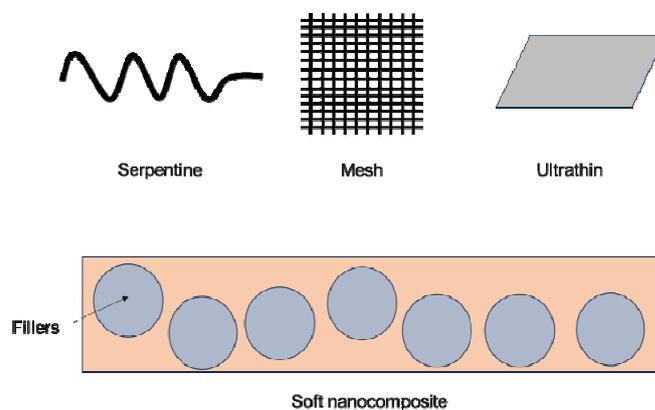


Figure 1. Mechanical designs incorporating soft materials to achieve softness

This review aims to provide a comprehensive overview of the state-of-the-art in soft bio-implantable electronics, framed by three major perspectives. First, we examine clinical needs across key medical domains, identifying scenarios where conventional rigid devices fail to meet long-term performance

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and safety requirements. Second, we explore potential materials and device design strategies, emphasizing how the integration of novel material platforms with optimized architectures can yield mechanically compliant yet functionally robust implants. Third, we analyze the mechanical properties of soft materials in the context of biological integration, focusing on strategies to ensure durability, stability, and bio-functionality in dynamic physiological environments. We conclude with a discussion of the translational challenges such as regulatory pathways, manufacturing scalability, and long-term biocompatibility that must be addressed to bring these innovations into routine clinical practice.

Clinical needs for soft bio-implantable electronics

The development of soft bio-implantable electronics represents a paradigm shift in the field of biomedical engineering, offering a novel class of platform for continuous, precise, and patient-oriented healthcare. Unlike conventional rigid implants that often cause mechanical mismatch with soft biological tissues, leading to inflammation, fibrosis, or device failure, soft bioelectronics leverage novel materials and device architectures that are stretchable, flexible, and even bioresorbable, allowing them to conform intimately to the surfaces of internal organs, muscles, and neural tissues. This biophysical compatibility enables long-term implantation with minimal immune response, a critical requirement for reliable sensing and therapeutic operation *in vivo*. The clinical needs driving this technological evolution are substantial and diverse, spanning a wide spectrum of medical domains including cardiology, neurology, gastroenterology, musculoskeletal rehabilitation, and chronic disease management. For instance, in the cardiovascular system, there is an urgent need for implantable devices that can continuously monitor electrophysiological activity, detect arrhythmias, and deliver pacing or defibrillation without invasive leads or rigid substrates that can damage tissue (Figure 2). Soft electronics, fabricated using materials like polyimide, PDMS, or silk fibroin, can wrap conformally around the epicardium or endocardial surfaces, enabling real-time monitoring or therapeutic stimulation with minimal physical burden on the patient (4). Similarly, in neurological disorders such as epilepsy, Parkinson's disease, or spinal cord injury, soft implantable interfaces offer a new level of precision in both neural recording and targeted stimulation (5). These devices can be placed directly on the cortex, spinal cord, or peripheral nerves, and owing to their tissue-mimetic mechanical properties, they maintain intimate contact with neural structures even as the tissue moves, expands, or contracts.

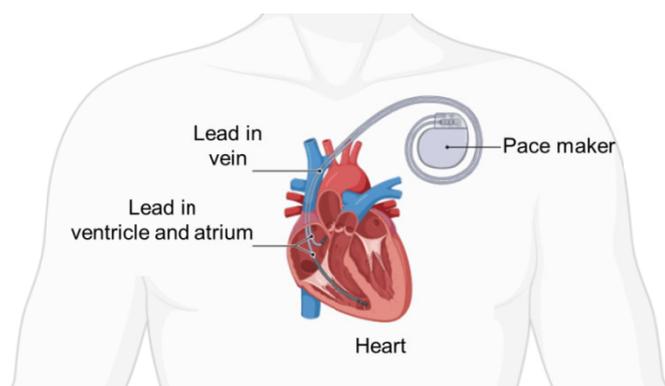


Figure 2. Conventional pace maker

This dynamic compatibility is essential for high-fidelity signal acquisition and localized neuromodulation, both of which are central to the success of closed-loop bioelectronic medicine systems. Furthermore, gastrointestinal disorders like gastroparesis or inflammatory bowel disease could greatly benefit from soft implantables that can monitor pressure, pH, or motility across various regions of the GI tract, or deliver localized stimulation to restore function, all while safely passing through or remaining *in situ* without damaging delicate mucosal surfaces. In musculoskeletal applications, soft electronic patches and injectable mesh devices are being explored for localized muscle stimulation, regenerative electrical fields, or real-time load monitoring, particularly in patients recovering from orthopedic surgeries or with degenerative conditions. Beyond these organ-specific applications, the broader trend toward personalized and remote healthcare has elevated the need for implantables that can operate autonomously, communicate wirelessly, and even degrade harmlessly after their functional lifetime. Patients with chronic conditions such as diabetes, hypertension, or cancer require long-term monitoring of biomarkers that can only be accurately captured at the tissue level; soft bioelectronics embedded under the skin or within body cavities provide a non-disruptive route for achieving such diagnostics with continuous data feedback. To meet these clinical expectations, the field has evolved from merely soft packaging of rigid components to fully integrated soft systems, where every functional element sensor, electrodes, interconnects, power sources, data transmitters is engineered from mechanically compliant or transient materials. Power management remains a key bottleneck in long-term implantation, prompting exploration into wireless power transfer via inductive coupling, energy harvesting from body motion, or the integration of miniaturized biofuel cells that convert glucose into electricity.

Data transmission also faces constraints in implantable environments, where conventional RF communication is limited by tissue absorption; as such, new strategies using ultrasonic or near-field communication, along with on-device signal processing to reduce data load, are being actively pursued. Another crucial aspect is the integration of sensing modalities tailored to specific clinical markers electrophysiological, biochemical, or mechanical. For example, multiplexed sensors capable of detecting neurotransmitter levels, inflammatory cytokines, or oxygen saturation can provide a comprehensive picture of tissue health, guiding timely interventions. Moreover, soft electronics can be designed for bidirectional function, simultaneously sensing and delivering stimuli, which is foundational for closed-loop therapeutic systems. An emerging area is bioresorbable electronics devices that naturally degrade after fulfilling their purpose, eliminating the need for surgical removal. These are particularly suited for temporary monitoring during recovery from surgery or trauma, or for delivering timed therapeutic effects such as electrical stimulation for wound healing. Clinically, this reduces risk, improves patient compliance, and expands the potential for electronic medicine in resource-limited or outpatient settings. The success of soft bio-implantables, however, depends not only on their materials and functionality but also on their manufacturing scalability, sterilization stability, and regulatory pathway. Scalable fabrication methods such as soft lithography, screen printing, and roll-to-roll processing are enabling the production of complex yet flexible devices (Figure 3).

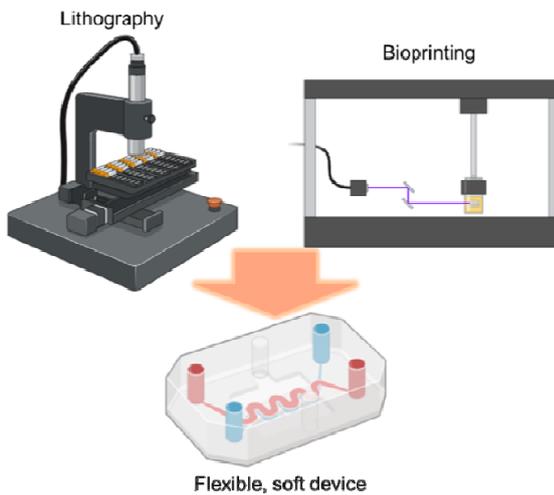


Figure 3. Scalable fabrication for implantable devices based on soft materials

Sterilization techniques must preserve the integrity of soft polymers and bioresorbable components, often requiring low-temperature or chemical-based approaches. From a regulatory standpoint, the combination of novel materials, transient behavior, and integrated wireless systems challenges traditional device approval frameworks, underscoring the need for collaborative pathways involving researchers, clinicians, and regulatory bodies. Ethical considerations also arise, particularly in long-term neuro-monitoring or behavior-modifying applications, where patient autonomy, data privacy, and informed consent must be carefully addressed. Despite these challenges, the clinical momentum and technological maturity of soft bio-implantable electronics are rapidly converging. Recent clinical trials and first-in-human demonstrations such as transient cardiac monitors, bioresorbable neural probes, and flexible gastric pacemakers have shown the feasibility and safety of these systems, marking a critical inflection point for their transition into routine medical practice. As the global healthcare landscape shifts toward preventative, personalized, and decentralized care, the role of soft bioelectronics will only become more prominent, offering a powerful interface between human physiology and digital medicine. Future efforts must continue to integrate emerging advances in synthetic biology, machine learning, and microfluidics to create intelligent, adaptive, and multifunctional platforms that respond dynamically to the body's needs. In summary, soft bio-implantable electronics, enabled by innovative materials and design strategies, directly address pressing clinical needs across multiple organ systems and disease categories. They offer a pathway toward more effective, less invasive, and continuously adaptive healthcare interventions, making them one of the most promising frontiers in 21st-century medical technology. In the next session, we will review about soft functional materials and their mechanical properties followed by systemic applications enabled by those materials.

Potential material and design for soft implantable system

The development of soft implantable systems necessitates a paradigm shift in both material selection and device architecture. Unlike conventional implants that rely on rigid materials such as metals and ceramics, soft systems demand materials that exhibit mechanical compliance comparable to native biological tissues. This compliance not only minimizes mechanical mismatch at the tissue-device interface but also

reduces chronic inflammatory responses and enhances long-term biocompatibility. Among emerging materials, elastomers such as polydimethylsiloxane (PDMS), Ecoflex, and thermoplastic polyurethanes (TPUs) have garnered significant attention due to their tunable mechanical properties, chemical stability, and ease of fabrication. Hydrogels, with their high-water content and tissue-like elasticity, also show promise, particularly in applications requiring intimate coupling with soft tissues such as neural or cardiac interfaces. These materials exhibit exceptional softness and dynamic deformation similar to biological tissues, effectively minimizing mechanical stress (6). Beyond intrinsic material properties, structural design plays a pivotal role in achieving functional robustness. Strategies such as serpentine interconnects, fractal geometries, and mesh-like scaffolds allow traditionally rigid electronic components to deform with minimal strain localization, enabling reliable operation under physiological motion. These mechanical patterns effectively absorb external mechanical stress through deformation of their complex structures. Additionally, multi-layered architectures incorporating encapsulation layers, conductive traces, and functional interfaces must be carefully engineered to withstand degradation caused by prolonged exposure to ion-rich and corrosive bodily fluids. Recent advances in bioresorbable materials have enabled the development of temporary implants that safely degrade *in vivo*, eliminating the need for surgical retrieval. For example, bioresorbable pressure sensors and hydrogels have been demonstrated to monitor physiological parameters or replace vitreous fluid and then dissolve within weeks to months inside the body (7). Metal-based bioresorbable implants, such as magnesium- or zinc-based alloys, are being actively explored for orthopedic and cardiovascular applications, offering mechanical strength and controlled degradation over longer periods. In addition, stimulus-responsive systems allow precise control over the device's functional lifetime through triggered degradation. These examples underscore the importance of tailoring both materials and structural design to the specific requirements of each biomedical application. Incorporating microfabrication techniques such as soft lithography, 3D printing, and laser patterning enables high-resolution control over device geometry, facilitating both functionality and scalability. Thus, the integration of novel material platforms with optimized design strategies represents a critical foundation for the next generation of soft, bio-integrated implantable devices.

Mechanical properties of soft materials

The advent of bio-implantable electronics has revolutionized the way physiological signals are monitored and therapeutically modulated within the human body. Traditional rigid implants, while effective in some contexts, often suffer from mechanical mismatch with soft biological tissues, leading to discomfort, immune responses, and limited long-term stability. To address these challenges, recent research has focused on the development of soft bioimplantable electronics devices engineered from materials with mechanical properties that closely match those of living tissues. These soft platforms enable intimate, conformal integration with diverse organs, minimizing tissue damage and inflammation while maintaining stable, high-fidelity functionality over extended periods. This convergence of materials science, device engineering, and biomedical design has opened new horizons for implantable systems targeting critical organs such as the heart, brain, peripheral nerves, and kidneys.

In the cardiac domain, significant strides have been made with the development of OBXene patches incorporating MXene-based low-impedance electrodes (8). These patches conformally adhere to the epicardium of the left ventricle and have demonstrated real-time spatial mapping of electrophysiological activity along with wireless pacing capabilities in both rodent and porcine models. Notably, this system integrates recording and pacing functions within a closed-loop framework, enabling responsive therapeutic intervention. Complementing this, a recent 2024 ACS Nano review highlights the promise of intrinsically soft nanocomposite devices comprising conductive nanoparticles dispersed within elastomeric matrices which also exhibit excellent conformal attachment to the heart surface and facilitate high-quality electrical signal mapping paired with feedback stimulation (9). Moving to the brain, the Charles Lieber group has pioneered injectable mesh electronics capable of being delivered through a minimally invasive 0.1 mm needle. Once introduced, these ultraflexible mesh structures unfold within brain tissue, permeate the neural matrix, and enable stable, chronic neural signal recording over several months (10). Crucially, histological analyses reveal an absence of chronic immune activation, with no significant astrocyte or microglia accumulation, indicating excellent biocompatibility. This technology sets a new benchmark for long-term brain-machine interfaces by allowing multi-year tracking of individual neurons without eliciting reactive gliosis, thereby preserving native tissue architecture and function. In the peripheral nervous system, the electronic dura mater or e-dura technology developed by the Lacour group represents a landmark soft implant (11).

This system integrates PDMS-based stretchable electrodes with fluidic channels to provide combined electrical and pharmacological stimulation. When applied in spinal cord injury models, e-dura not only maintains mechanical integration with host tissue but also facilitates significant motor function recovery. Furthermore, a 2024 review in *Advanced Functional Materials* details the emergence of multimodal soft implants that combine electrical, optical, and fluidic delivery functionalities, enabling selective modulation of sensory fibers in nerves such as the sciatic nerve highlighting the expanding multifunctionality of soft bioelectronics (12). Although still in nascent stages, a well-cited review on soft hydrogel nanocomposites underscores the suitability of hydrogel-based soft sensors for monitoring renal blood flow and urine dynamics, attributing their effectiveness to key properties such as tissue affinity, injectability, self-healing, and biodegradability (13).

This review further emphasizes the broad applicability of these materials across various electroactive tissues, including the heart and peripheral nerves, in addition to renal structures. Lastly, hydrogel-based neural stimulation and interface technologies have garnered substantial attention for their exceptional softness and biocompatibility. For example, a study published in *Nature Biomedical Engineering* demonstrated a hydrogel-based microelectronic device capable of localized low-voltage neuromodulation without causing tissue damage, exemplifying how soft materials can enable safe and effective neural therapies (14). Together, these diverse demonstrations illustrate that soft-material-based bio-implantable electronics can be successfully tailored for a wide range of organs including the cardiac epicardium, brain cortex, peripheral nerves and spinal cord, and renal vasculature

through various design strategies such as stretchable nanocomposites, injectable mesh electronics, hydrogels, and fluidic PDMS architectures. These approaches have consistently achieved superior tissue compatibility, long-term operational stability, multifunctional capabilities, and wireless or closed-loop operation. For comprehensive review purposes, it is recommended to organize these examples into detailed subsections by organ system, systematically summarizing the material compositions, implantation techniques, functional performances, and biological response evaluations to provide a clear and integrated overview of this rapidly advancing field.

Conclusion

Advances in soft, bio-implantable electronics are redefining the landscape of healthcare technologies by enabling intimate, long-term integration with biological tissues. Through the convergence of material science, device engineering, and clinical insight, next-generation implants are achieving unprecedented levels of mechanical compliance, functional stability, and biocompatibility. This review has highlighted the clinical motivations driving the need for soft implantables, the materials and design strategies underpinning their development, and the critical mechanical considerations necessary for ensuring their performance in complex physiological environments. Despite these promising developments, several translational barriers remain, including the need for standardized regulatory pathways, scalable and reproducible manufacturing processes, and thorough validation of long-term biosafety. Addressing these challenges will be essential to realize the full clinical potential of bio-implantable electronics and to enable their widespread adoption in personalized and precision medicine.

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