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Review Article

Smart Implants: Transforming Drug Delivery Systems

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ABSTRACT

Smart implants represent an advanced class of biomedical devices integrating sensing systems, microelectronics and targeted drug release mechanisms. These technologies enable adaptive, real time drug delivery based on physiological inputs, thereby improving therapeutic outcomes, minimizing side effects, and enhancing patient compliance. A comparative evaluation of current smart implants systems was carried out with respect to their drug delivery efficiency, biosensing capabilities and personalized medicine applications. Innovations in material science, miniaturization and energy harvesting techniques were reviewed to determine their role in overcoming technical limitations. The role of wireless connectivity, wearable integration and AI assisted analytics was assessed to understand their contribution to real time monitoring and controlled drug release. Smart implants demonstrated high therapeutic potential, particularly for chronic diseases such as cancer, diabetes, cardiovascular disorders and chronic pain. Integrated biosensors and microelectronic systems enabled continuous monitoring and adaptive drug delivery, resulting in greater precision and reduced need for manual intervention. The use of biocompatible materials and self-powered systems further enhanced device performance and longevity. AI-enabled predictive algorithms and wireless communication significantly improved real-time decision-making and healthcare connectivity. These advancements collectively suggest reduced hospitalization, improved access to continuous therapy, and enhanced patient specific treatment plans. Smart implants offer a transformative approach to modern healthcare through real-time, personalized, and minimally invasive drug delivery systems. With continuous progress in nanotechnology, biosensor design, and AI assisted treatment prediction, smart implants are expected to remain at the forefront of advanced medical therapies for decades. They hold strong potential for reducing treatment burden, improving accessibility, and providing highly individualized care.

Keywords: Drug delivery, Nanotechnology, Personalized medicine, Smart implants.

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INTRODUCTION

The Drug Delivery Systems (DDS) are novel technologies design to deliver drug compounds in a controlled, targeted and efficient manner to body sites for maximum therapeutic benefits with minimized side effects (Ezike *et al*., 2023). The traditional delivery of drugs by oral route, intravenous injections, topical applications and intramuscular injections comprises each of these methods to some benefit but also with some drawbacks (Adepu *et al*., 2021). Oral is the more accessible and user-friendly route burdened with poor bioavailability and possibly spasmodic absorption, while another means of administration at least more direct, constitutes administration by the means of injections, and that too invasive involving professional healthcare administration (Alqahtani *et al*., 2021). In more recent years, more sophisticated DDS have come into existence-impregnated controlled drug release systems, targeted efficient treatments and controlled drug delivery to specific sites (Dave *et al*., 2017). These are technologies coupled with the use of biotechnology, nanotechnology and material sciences that create solutions to treat more accurately diseases of a chronic nature, infection and such ailments requiring long-term treatments (Fayzullin *et al*., 2021). Nowadays, implantation takes the forefront of medicine, meaning a medical device implanted in the body to release long-term doses of drug. Such implants could be subcutaneous, intravascular or implanted in the tissues or organs and pose immense benefits in the delivery of drugs in the local and systemic manner (Faudoa *et al*., 2019).

Implants can minimize the frequency of administration, improving patient compliance, which is especially important in conditions such as diabetes, cardiovascular diseases and cancer (Bazaka *et al*., 2013). Implants will avoid frequent injections or intake of pills by continuous drug delivery. A well-designed implant releases medication in a controlled manner, adjusting to a patient's changing needs and minimizing drug waste hence reducing side effects (Blackshear *et al*., 1979). Some implants are designed to even monitor physiological parameters such

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as glucose levels and respond appropriately by modulating the release of the drug for personalized treatment. Continuous drug delivery by an implant and response to physiological conditions make them indispensable in improving the treatment outcome, especially in patients needing long-term medication (Yogev *et al*., 2023).

Smart drug delivery systems carry implant technology one step further, incorporating sensors, electronics, and advanced materials that will permit the device to take active action in response to the body's needs (Cheung *et al*., 2023). Capable of releasing drugs at controlled rates, smart implants can monitor real-time biological signals and self-adjust drug delivery in accordance with the changing condition of a patient. A smart implant can instance, produce insulin autonomously when the blood sugar level rises in a diabetic patient thus eliminating the need for intervention by the latter. Smart DDS thus allows personalized medicine whereby treatment can be delivered according to individual needs, which would help not only in enhancing treatment outcomes but also in better adherence by the patient. The precision in dosage avoids the normal overdose or under-dose risks seen with the standard techniques of drug (Cicha *et al*., 2022). Furthermore, real-time monitoring allows feedback loops that will always promote more informed clinical decision-making thus making timely interventions possible. Minimally invasive implants may come as smart implant devices, offering adaptive health solutions where sustained and personalized treatment approaches are indispensable, especially in oncology, diabetes management and pain treatments. Their potential to optimize drug release, monitor therapeutic responses and improve quality of life positions them as a key technology for the future of medicine (Goetz *et al*., 2018). Figure 1 illustrates various drug delivery systems designed to enhance the targeted, controlled and efficient administration of therapeutic agents.

METHODOLOGY

A structured narrative method was applied to this review and provided an opportunity to find and synthesize the material concerning the topic of smart implants in drug delivery systems. In pubmed, scopus, web of science, science direct and google scholar, a comprehensive search was conducted and the keywords included: smart implants, implantable drug delivery systems, biosensor-integrated drug delivery, closed-loop drug delivery, implantable biosensors, nanotechnology in implants, AI in drug delivery and personalized implantable therapeutics. Only peer-reviewed articles and reviews in english accentuating implantable systems that have capability of delivering drugs were incorporated and articles not peer reviewed, abstracts of conferences, studies that were not related to smart implantable therapeutics and traditional non-adaptive drug delivery systems were excluded. Following the screening of duplicates and titles and abstracts, full-text articles were evaluated on their eligibility and relevant studies were subjected to qualitative analysis to summarize the materials, sensing mechanisms, microelectronics integration, clinical applications and future perspectives.

BACKGROUND ON TRADITIONAL DRUG DELIVERY METHODS

Oral delivery is the most common mode of drug delivery encompassing a number of dosage forms like capsules, tablets and liquids. Convenience and patient compliance are the major benefits of oral delivery as it is straightforward and non-penetrating compared to any of the routes of drug delivery (Abyzova *et al*., 2023). It also offers scope for mass production and economical distribution. Yet there exist numerous challenges related to this mode, primarily low bioavailability owing to drug degradation in the stomach and first-pass metabolism in the liver. Such factors have the ability to diminish the effectiveness of drugs such as antibiotics or cancer treatments, often requiring greater doses or different routes of delivery in order to achieve the therapeutic effect. Injection type systems such as subcutaneous, intramuscular and intravenous injections remain unaffected by gastrointestinal absorption and hepatic first-pass metabolism, that will in effect translate to superior systemic levels of drugs that otherwise enjoy very poor oral bioavailability (Maurya *et al*., 2024). Figure 2 depicts the various routes through which drugs can be administered, including oral, parenteral, topical, transdermal and implantable systems. These delivery pathways enable targeted therapeutic action by determining the onset, intensity and duration of drug response.

Among these routes, the fastest and most consistent onset of action is provided by intravenous injection, and the subcutaneous and intramuscular routes permit administration in larger volumes to achieve controlled release of therapeutic proteins like vaccines, insulin and biologics over time. Those are painful injections sometimes even more so if they need to be done quite regularly that is done by professionals only and not available with the immediacy of near access and convenience a majority of the population might generally accept. This could be frustrating in the instance of many daily injections in patients of chronic conditions, like in diabetes. Second treatments of the biologics that could also be a solution bear the pain, and it reduces the compliance of the patient to a great degree (Zhou *et al*., 2015). Topical and transdermal drug delivery systems entail the delivery of drugs directly to the skin and are an alternative to the routes of drug administration for the delivery of active therapy locally and systemically. Topical systems deliver drugs for diseases that reside locally in the skin like eczema or acne, and transdermal patches deliver drug continuously and in a controlled manner to the bloodstream for systemic active action. Examples include hormone replacement therapies or patches of nicotine (Kim *et al*., 2024). Transdermal systems are also very patient-convenience and they bypass gastrointestinal side effects of the drugs including metabolism in the liver. Yet they have limited permeability to the skin and only small or in the right formulation of drugs transit across the skin. Skin irritation over the long term could also result from patches and the drug efficiency could be altered by the condition of the skin, temperature and the drug formulation (Narasimha *et al*., 2010).

SMART IMPLANTS

Implants

To substitute, assist or augment biological structures there exist medical devices or materials implanted surgically within or on the body. Such implantable devices or materials may be used to release drugs, monitor the body's functions, substitute absent body parts (e.g., joint replacements or dental implants) or achieve cosmetic alterations (Benson *et al*., 2019). Silicone, titanium or polymer-based implants are designed to match the body as safely as possible while reducing the likelihood of infection or rejection. The longevity, usability and compatibility of the implantable devices are steadily being improved by advances in medical technology, also offering innovative treatments for a range of diseases (Zhang *et al*., 2021).

Smart Implants

Smart implants refer to a group of implantable devices with the intelligent capabilities of sensing the alterations in the human body, processing the data and acting upon them to provide maximum therapeutic outcomes. Such devices contain embedded sensors, microelectronics and power sources and possibly interacting with the biological systems. These implants not only have the ability to release therapeutic agents like drugs or hormones but also to modify the mode of action in accordance with the body's instantaneous requirements. Therefore, closed-loop systems automatically sense the alterations in the body and respond to them towards a much more accurate personalized therapy. It makes it possible for the smart implants to serve as substitutes for traditional drug delivery systems in adaptive therapies, chronic disease treatments, pain, diabetes, neurologic diseases and even cancer (Quick *et al*., 2024).

Types of Smart Implants

Table 1 presents an overview of various types of smart implants along with their key functional features. It highlights differences in sensing abilities, drug delivery mechanisms, materials and clinical applications across each implant types.

Mechanism of Action

Mechanism of Sensing

Sensors on smart implants continuously observe various physiological signals, including glucose level, heart rate, blood pressure, or neural activity. Data collected by the sensors provides input to the subsequent action of the implants.

Data Analyzing and Processing

After they are sensed, microelectronics of the various implants analyze the data by employing sophisticated 'algorithms' that target interpreting data concerning the status of the bodies. An implanted glucose sensitive sensor for example perceives that there is the rise and fall of blood sugar and further controls the release of the medication (Whyte *et al*., 2022).

Actuation and Drug Delivery

As a result of data analysis, it will act on such activity initiation as drug release. A smart implant will release the insulin on the basis of the analysis on the threshold levels of glucose by taking evidence-based treatment at the precise location (Zhu *et al*., 2021).

Closed-Loop Systems and Feedback

Smart implants in operation involve a continuous monitoring of output in relation to physiological responses that undergo alterations. For instance, a smart pacemaker automatically adjusts pacing based on alterations in rhythm of the heart or the level of activity in order to deliver personalized and real-time care (Kim *et al*., 2024).

Wireless Communication and Remote Monitoring

The majority of smart implants will have wireless communication capabilities, whereby data will be transmitted to external devices like smartphones or healthcare monitoring systems. This will help patients and healthcare professionals to continuously observe implant and patient status from a remote location, minimizing the need for regular visits (Roy *et al*., 2022).

Powering the Implants

Powering the implant is also one of the challenges. Some of the techniques for energy harvesting include transforming body motion to electrical energy, biofuel cell energy from glucose or rechargeable batteries through external inductive recharging systems (Guo *et al*., 2018).

TECHNOLOGICAL FOUNDATIONS OF SMART IMPLANTS

Sensors and Microelectronics

Sensors

Smart implants depend on sensors to identify certain physiological or biological markers. These sensors come in two different categories:

Chemical Sensors

Glucose sensors used in the control of diabetes, for instance; quantify glucose concentration in blood or in interstitial fluid.

Physical Sensors

Physical sensors identify physical parameters such as temperature, pressure and heart rate. Some of the examples of physical sensors are pressure sensors, used to register intraocular or intracranial pressure and to enable timely intervention should the thresholds be surpassed (Ghazizadeh *et al*., 2024).

Microelectronics

Embedded microelectronic processes input from sensors via miniscule processors, memory and control circuits. The systems translate data from the sensors in real time and initiate drug release or stimulation events when required. Advances in nanotechnology and microfabrication allow ultra-small power-efficient devices, necessary in order to work in a power-limited environment (Liang *et al*., 2023).

Biocompatibility and Materials Used

Biocompatibility

Materials in smart implants must interact safely with the body without causing immune responses or toxicity. These materials also need to resist degradation over time to maintain functionality (Sufiyan *et al*., 2024). Table 2 summarizes the various biomaterials employed in smart implants, highlighting their functional roles in structural support, biosensing and controlled drug delivery. These materials including metals, polymers, ceramics and composites are selected for their biocompatibility, durability and ability to integrate with advanced electronic components.

Power Supply and Energy Harvesting

Smart implants certainly do need some quite reliable and long-life power supplies. Options will include:

- **Batteries:** Rechargeable lithium-ion batteries are the common usage but handicapped in regard to service life and size.
- **Energy harvesting:** Body movements are utilized to harvest energy - piezoelectric systems, or biological processes, biofuel cells.
- **Inductive Charging:** It refers to wireless recharging via electromagnetic fields to make the process not invasive.
- **Wireless Power Transfer:** Provides energy from external devices to allow uninterrupted operation without the necessity to replace batteries (Dubey *et al*., 2017).

Data Communication and Feedback Mechanism

Data Communication

Smart implants also have the ability to transmit physiological data wirelessly to some external device, for example, a smartphone or to healthcare systems directly. Particularly in some instances glucose levels via an insulin pump will be monitored using a smartphone app and even used to initiate real-time adjustments to the treatment (Billah *et al*., 2024).

Feedback Mechanisms

Such devices can get external commands, like a pacemaker adjusting the parameters of pacing according to feedback. They can also alert in case of abnormal results or medication shortages (Kurtz *et al*., 2007).

Secure Transmission

Such protocols and related standards such as HIPAA encrypt sensitive healthcare data. Communications between the implant and external system are therefore secure, ensuring the confidentiality of a patient's data (Kalambettu *et al*., 2014).

The technological basis of smart implants is also extremely intricate and multifaceted, involving sensing, microelectronics, material, energy systems and communication technologically seamlessly integrated. As the applications and functions become increasingly updated with the times, there will be further growth of smart implants into the new arena that previously envisioned: precision medicine and long-term patient management (Wang *et al*., 2022).

APPLICATIONS OF SMART IMPLANTS IN DRUG DELIVERY

Smart implants represent one such extremely new drug delivery approach that promises never-before-seen precision, efficiency and patient compliance. With embedded sensors, microelectronics and adaptive control systems, such implants could be made into intelligent devices that can self-regulate medication delivery in a precise, targeted manner and only when needed (Cappon *et al*., 2019). Figure 3 depicts smart implants enhance drug delivery by enabling precise, real-time, personalized and controlled therapeutic release for improved patient outcomes.

Targeted Drug Delivery

Smart implants are designed to deliver very specific amounts of medication to specific sites in the body, with the aim of minimizing side effects while maximizing therapeutic effects.

Localized delivery

It has used the technique of using implants in cancer therapy to deliver chemotherapy drugs when they come in contact with the specific conditions of the tumor such as hypoxia or low pH. Reducing the systemic toxicity of ocular implants targeted at glaucoma or macular degeneration can deliver just as successfully to the retina or vitreous humor.

Biological Targeting

They could also be made to respond to cellular targets including receptor binding sites in such a manner that the drug is delivered to targeted, disease cells. This will be of great benefit in the instance of infectious and autoimmune diseases in which targeted delivery of the drug to the infected or the targeted tissues will lead to better outcomes with less interference from the healthy tissues (Dogra *et al.*, 2024).

Controlled and On-Demand Release

Smart implants have controlled and responsive drug release to avoid fluctuations in drug levels and side effects.

Sustained Release

Implants release the working ingredient at a steady rate over time, yielding consistent therapeutic action. An example of such delivery mechanism is the continuous delivery of insulin at a rate based on a continuously monitored real-time glucose level with the aid of a related device.

On-Demand Release

Pain relief implants deliver analgesics only when they are needed, hence maximizing the feeling of comfort and minimizing overuse. Adaptive systems would hence, in accordance with actual physiological oscillations such as pain biomarkers or neural signals, adjust the drug release rate in real time.

Controlled release minimizes dosing frequency, enhances compliance with therapy and lacks the peaks and troughs of drug concentration characteristic of the classical approaches (Joosten *et al.*, 2020).

Personalized Medicine and Adaptive Dosing

Smart implants can therefore serve this purpose of personal dosages based on individual patients, thus making drug delivery tailored to their needs in real time.

Adaptive Dosing

Implants alter the amount of drug delivered according to physiological feedback. Insulin pumps for example can adjust the amount of the drug they dispense in accordance with increasing and decreasing blood glucose levels to avoid errors where the individual might overlook administering the correct amount through a standard injection.

Customized Cancer Therapy

The implants deliver chemotherapeutic drugs based on the size of the tumor, metabolic pattern, or genetic markers to achieve precision in dosing and to preclude overtreatment or under treatment (Hyland *et al.*, 2021).

Long-Term Drug Monitoring

Continuous Monitoring

The implant continuously tracks drug levels and biological markers to deliver the best therapeutic levels and alert patients or clinicians when dosage needs to be modified.

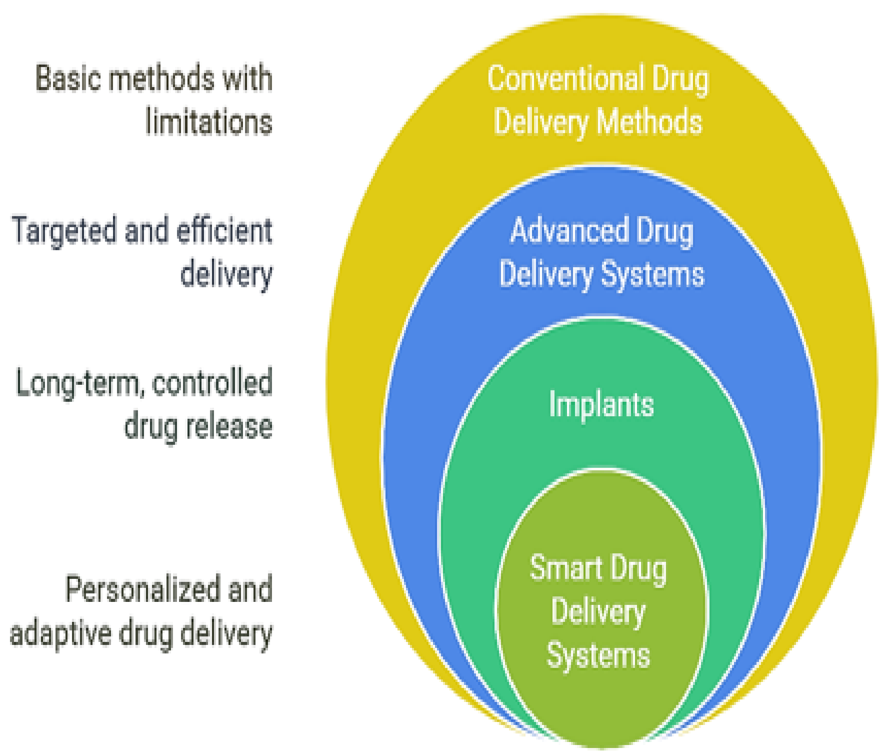

Figure 1: Drug Delivery Systems (Goetz *et al*., 2018).

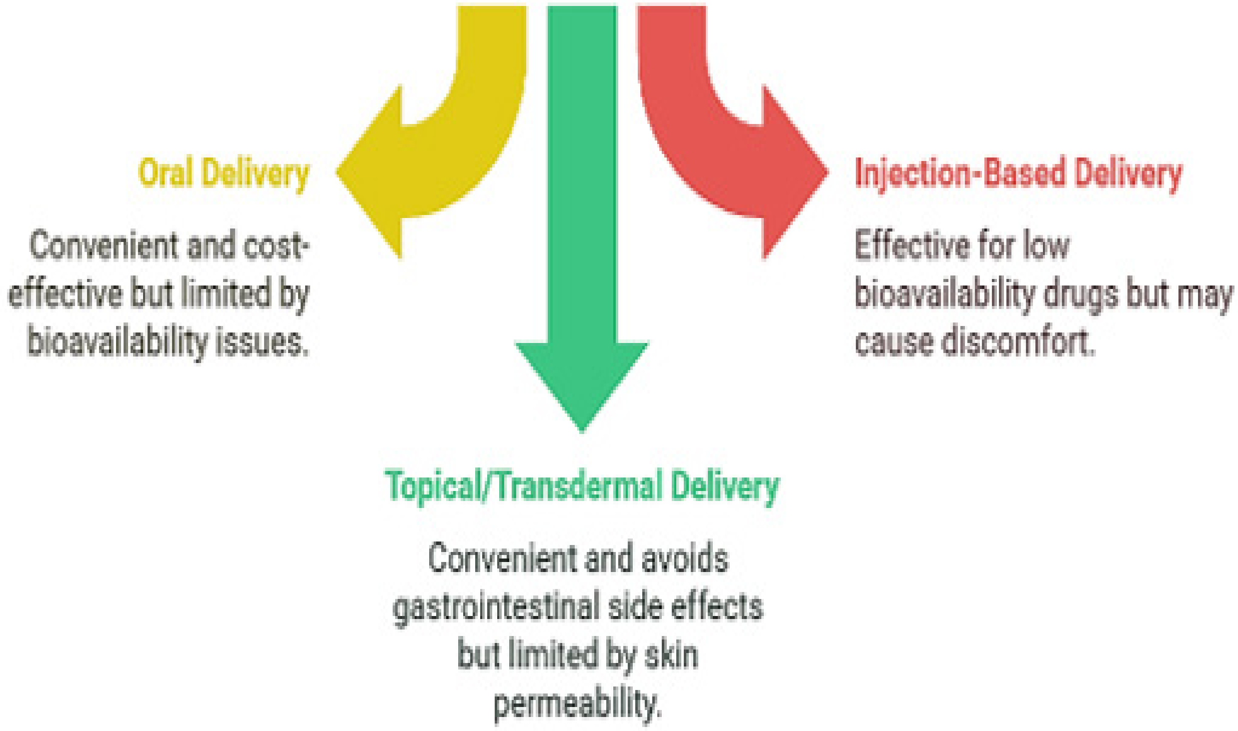

Figure 2: Routes of drug delivery (Maurya *et al*., 2024).

Remote Monitoring

The capability to transmit the data wirelessly to healthcare professionals minimizes the patients' trips to the hospitals and hence enables timely interventions.

The implant ensures patients remain on top of things, particularly in diseases such as diabetes, cardiovascular diseases or HIV by tracking medication levels and compliance (Omidian *et al*., 2023).

The various applications of drug delivery with smart implants have significant implications for virtually every aspect of therapy of a vast number of diseases. The devices through targeted delivery, controlled, demand-driven release and personalized dosing hold the promise to enhance therapeutic responses, increase compliance and minimize side effects (Krittanawong *et al*., 2021). The capability of long-term monitoring then allows for ongoing feedback towards adaptive therapy to maximize patient outcomes over time. With the progress of technology, the applications will only broaden further, providing increasingly more accurate, efficient and patient-specific drug delivery solutions (Keller *et al*., 2017).

CHALLENGES AND LIMITATIONS OF SMART IMPLANTS

Smart implants promise revolutionizing drug delivery and healthcare but there are many challenges to the dream materializing into a common phenomenon. Technical challenges involve powering and energy efficiency, miniaturized devices need long-life and energy-efficient systems (Covaci *et al*., 2020). Existing energy-harvesting technologies using piezoelectric devices remain under development. Integration of drug reservoir, processor and sensors into a small functional device is another likely to remain as a major obstacle (Amirtharaj *et al*., 2022). Durability and dependability are also critical as such implants need to withstand the variable conditions of the human body without failing over a very extended period of time (Nuss *et al*., 2008). Biocompatibility is naturally key to preventing immunity and rejection of the implant. Biocompatible materials such as titanium or silicone will thus cause minor inflammation while the implant made of bioresorbable material will have serious issues of controlling the degradation rate in synchronization with stable release rate of the drug (Sharma *et al*., 2023). Other dangers include the possibility of infection and biofilm formation, forgery of which will be prevented through special coatings and antibacterial substances (Djordjevic *et al*., 2023). Extended time of approval and high-costed clinical trials hinder market entry for new implants. Ethical concerns involve issues of patient privacy, data security and ongoing surveillance, compromise of which will be made possible by entry into the purview of unsanctioned personnel of sensitive personal health data. Biological processes may be controlled by active implants raising the question of autonomy and privacy concerns (Ozdemir *et al*., 2019). The high manufacturing cost, coupled with the lack of reimbursement and insurance, may preclude access to the smart implant, particularly in the poorer areas. Socio-economic factors will pose healthcare inequalities to bring about healthcare issues in accessing the desirable technologies and despite the advances in material science and engineering, policy-making has been relentless and promises vast solutions. This thus creates a brighter road ahead in which the implant technologies could define the new face of healthcare (Sim *et al*., 2021).

THE FUTURE OF SMART IMPLANTS IN DRUG DELIVERY

Advances in material science, nanotechnology, AI and biomedical engineering, the smart implants in the future will increasingly contribute to personalized medicine and drug delivery. Such advancements include the drug delivery through development of nanotechnology, miniaturization of the implant, enhancing the implant's efficiency of operation, targeted drug delivery and also the fabrication of biodegradable material to avoid the need for surgery to retrieve them (Abaszadeh *et al*., 2023). More sophisticated sensing will continuously track vital signs, metabolic shifts and genetic markers to enable real time adjustment of therapy (Wang *et al*., 2023). Such implants will also communicate with additional healthcare technologies such as wearables like smartwatches and continuous glucose sensing wearables that exchange data to make seamless drug release adjustments (Masoumian *et al*., 2023). The implant devices also communicate with the AI-driven algorithm to optimize doses and forecast health patterns. Through telemedicine, it could also be monitored from a distant location without a doctor visit. Yet, there exist challenges to their widespread acceptance. The time consuming and costly agency approval by the likes of the FDA and the expense and affordability create space for a limited take-up of innovative technologies such as 3D-printing promise in that regard. Education and enlightenment of healthcare workers and patients on the manner in which they work correctly create the need to inspire confidence in them. Ultimately, also, health systems will need to invest in the proper infrastructure to manage the amount of data and integrate the devices into existing organizational routines. To mitigate such challenges, the intelligent implant will be the crux of personalized medicine, delivering more efficient and accessible healthcare solutions (Yogev *et al*., 2023).

CLINICAL APPLICATIONS OF IMPLANTS

Smart implants revolutionize the management of chronic diseases by offering accurate, adaptive drug delivery that overcomes the drawbacks of conventional treatments. For cancer therapy, smart implants deliver medication directly to tumors to minimize systemic toxicity. They release drugs based on tumor-specific stimuli such as pH or temperature and can be remotely controlled by external heating or light for more controlled delivery. This targeted delivery reduces side effects such as nausea and

Table 1: Types of smart implants and their key features.

Types of Smart Implant	Description	Example Applications	Key Features
Drug-Delivery Implants	Implants that release medication at controlled rates over extended periods, responding to physiological signals.	Insulin pumps, contraceptive implants, hormone therapy, pain management.	Controlled release, real time feedback, continuous drug delivery (Quick *et al.,* 2024; Oehrn *et al.,* 2024).
Neural Implants	Implants that interact with the nervous system to treat neurological conditions by delivering electrical pulses.	Deep Brain Stimulators (DBS) for Parkinson's disease, chronic pain treatment.	Modulates brain activity, adjustable stimulation based on real-time signals (Bruen *et al.,* 2017).
Biosensors	Implants with sensors that monitor biological markers like glucose levels, oxygen, heart rate, etc.	Glucose sensors for diabetes management, oxygen monitors.	Continuous monitoring, real-time data collection, therapeutic adjustment (Otero *et al.,* 2021; Ledet *et al.,* 2018).
Orthopedic and Prosthetic Implants	Implants designed for bone healing, joint monitoring, or to enhance prosthetics with real-time feedback.	Smart hip implants, prosthetic limbs with muscle signal detection.	Real-time monitoring, personalized care, feedback on joint movement (Jan *et al.,* 2023; Agarwal *et al.,* 2022).
Cardiovascular Implants	Devices that monitor heart function and adjust therapies based on heart rate or rhythm abnormalities.	Smart pacemakers, Implantable Cardioverter-Defibrillators (ICDs).	Heart rate adjustment, shock delivery, integration with external devices (Maron *et al.,* 2023; Woodring *et al.,* 2023).
Cancer-Related Implants	Implants that deliver drugs directly to tumors in response to changes in the tumor's environment.	Tumor-targeted drug delivery systems, implants for localized chemotherapy.	pH or temperature-sensitive drug release, monitoring tumor biomarkers (Goncharov *et al.,* 2024).

Table 2: Materials used in smart implants.

Material Type	Properties	Applications in Smart Implants	Biocompatibility Features
Polymers (e.g., PLA, PCL)	Biodegradable, flexible, easily molded, good mechanical properties.	Drug delivery systems, biosensors, scaffolds for tissue engineering, neural implants.	Biodegradable, non-toxic degradation products, minimal immune response.
Silicone	Flexible, durable, heat-resistant, non-reactive.	Pacemakers, insulin pumps, prosthetics, biosensors.	Non-toxic, low immunogenicity, widely used in medical devices (Zhang *et al.*, 2012).
Titanium	High strength, corrosion-resistant, biocompatible, lightweight.	Orthopedic implants, dental implants, cardiovascular devices (e.g., pacemakers).	Excellent biocompatibility, promotes osseointegration, minimal rejection response.
Hydrogels	Hydrophilic, high-water content, soft, and similar to natural tissue.	Controlled drug delivery, wound healing, tissue scaffolding.	Biocompatible, supports cell growth, promotes tissue regeneration (Maloney *et al.*, 2005).
Gold	Biocompatible, corrosion-resistant, electrically conductive.	Neural implants, biosensors, drug delivery microchips.	Minimal immune response, inert, non-toxic, well-tolerated in long-term implants.
Ceramics (e.g., Hydroxyapatite)	Bioactive, supports bone growth, high stiffness, chemically stable.	Bone regeneration scaffolds, orthopedic implants, drug-eluting implants.	Promotes osseointegration, biocompatible, non-toxic, used in bone repair (Ielo *et al.*, 2022).
Carbon-based Materials (e.g., Graphene, Carbon Nanotubes)	High mechanical strength, electrical conductivity, excellent thermal properties, biocompatible in some cases.	Biosensors, drug delivery systems, neural interfaces, energy harvesting for implantable devices.	Can be biocompatible with careful functionalization, enhances electrical performance in implants.
Stainless Steel (316L)	Corrosion-resistant, durable, high tensile strength.	Orthopedic implants, cardiovascular implants (e.g., stents), drug delivery devices.	Generally biocompatible, low risk of adverse reactions, used for structural support.
Magnesium Alloys	Biodegradable, lightweight, can be absorbed by the body over time.	Bone implants, drug delivery systems that need temporary functionality.	Biodegradable, supports tissue regeneration, reduces need for second surgery.
Ceramic Polymers (e.g., Poly(Lactic-Co-Glycolic Acid) (PLGA))	Biodegradable, controlled degradation rate, good for sustained release.	Drug-eluting implants, tissue scaffolds, controlled release devices.	Biocompatible, biodegrades into safe byproducts, often used for long-term drug release (Mondal *et al.*, 2019).
Polyetheretherketone (PEEK)	High strength, chemical resistance, biocompatible, radiolucent.	Spinal implants, orthopedic devices, bone scaffolds, drug delivery systems.	Biocompatible, provides mechanical support, widely used in load-bearing implants (Singh *et al.*, 2022).
Silicon Carbide (SiC)	Hard, chemically stable, biocompatible, excellent for high-temperature applications.	Neural implants, biosensors, semiconductors for implantable devices.	Low toxicity, biocompatible with long-term use in neural implants (Kraus *et al.*, 2012).
Tantalum	High corrosion resistance, biocompatible, radiopaque.	Orthopedic implants, cardiovascular devices, electrodes in neural implants.	Biocompatible, highly stable in the human body, used in load-bearing and implantable devices (Alizadeh *et al.*, 2019).

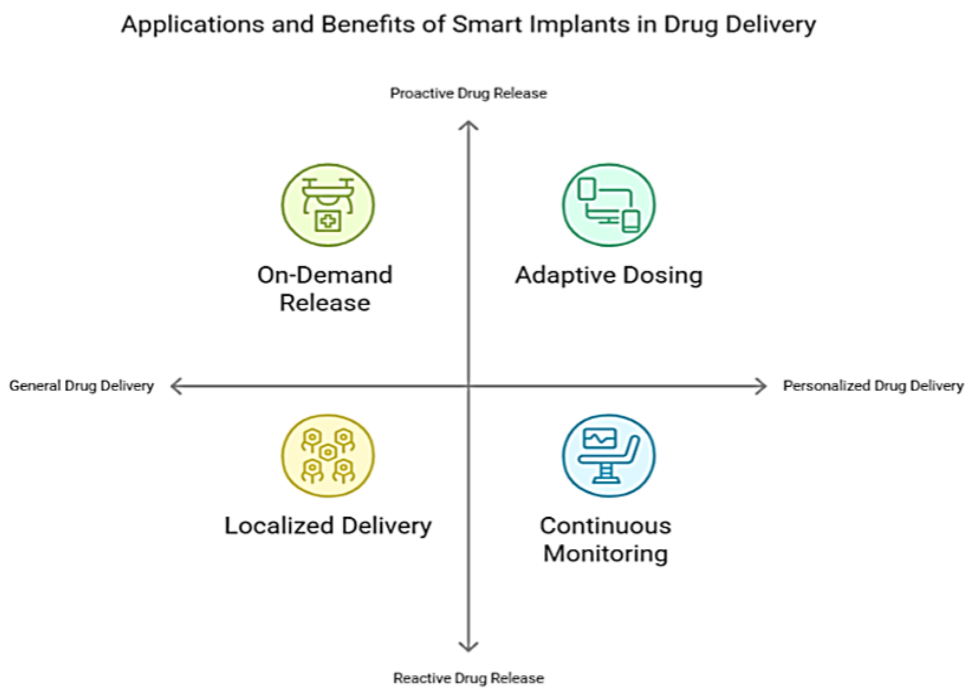

Figure 3: Benefits of smart implants in drug delivery (Cappon *et al*., 2019).

immunosuppression in the management of diabetes, and smart insulin implants repeatedly check blood glucose levels and adjust delivery of insulin in accordance with real-time fluctuations automatically. This removes the need for frequent injections, enhancing compliance and avoiding the complications of hyperglycemia or hypoglycemia (Shaik *et al*., 2023). For pain relief, neural implants such as intraspinal drug delivery and intrathecal drug delivery systems offer personalized and targeted relief (Simon *et al*., 2024). Smart variants adapt pain levels in real time to minimize the use of systemic painkilling medication and its attendant side effects, such as sedation. For cardiovascular disease, smart implants target delivery of medication to the affected region, such as antihypertensive for hypertension or anticoagulant in clotting risks. They also enable intra-cardiac delivery and real-time monitoring of cardiac parameters, enhancing the optimization of medication and long-term control of cardiac diseases. Such advancements in smart implants present more efficient, personalized, and less invasive therapies to enhance the outcomes of patients with chronic diseases (Bhattad *et al*., 2022).

CONCLUSION

Smart implants will revolutionize health care by providing optimal, controlled and tailorable delivery of the drug based on the prevailing physiological requirements. Such systems will couple high-level microelectronic and sensing elements with drug release mechanisms capable of revolutionizing therapeutic efficacy, minimizing side effects and maximizing patient compliance. Some of the applications in chronic diseases include cancer, diabetes and cardiovascular disease. It seems like while the device material becomes more sophisticated, the dimensions get reduced and energy will be harnessed to counter the challenges of the cutting-edge technology, regulation, compatibility issues, high costs and issues related to access remain a major issue concerning the intelligent implant. The possible effect on health and human lives is very high; such implants minimize the number of visits to the hospital, reduce the costs to the healthcare system and allow better delivery of health care to resource-poor communities. With continuous and responsive delivery, the enormous potential to enhance the quality of life of patients with chronic diseases cannot be overemphasized. Future research will call for the utilization of increasingly biocompatible materials, self-sustaining systems and the incorporation of AI and machine learning in personalized therapies. Nanotechnology and biosensors will increasingly optimize drug delivery and disease surveillance. Some of the issues to be addressed by cross-industry collaboration before such implants will become the pillars of the healthcare of the future include regulation and costs. Thus, the potential of smart implants to revolutionalize chronic disease management and personalized medicine is likely to be actualized as ever more innovation comes to the arena.

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ABBREVIATIONS

DDS: Drug delivery Systems; **AI:** Artificial Intelligence; **FDA:** Food and Drug Administration; **PLA:** Polylactic Acid; **PCL:** Polycaprolactone; **PLGA:** Poly(lactic-Co-Glycolic Acid); **PEEK:** Polyetheretherketone; **SiC:** Silicon Carbide; **ICD:** Implantable cardioverter-defibrillator; **DBS:** Deep Brain Stimulation; **3D:** Three-Dimensional; **ECG:** Electrocardiogram; **DNA:** Deoxyribonucleic Acid; **HPMC:** Hydroxypropyl Methylcellulose; **PMMA:** Polymethylmethacrylate; **DU:** Deemed University; **HIPAA:** Health Insurance Portability and Accountability Act; **HIV:** Human Immunodeficiency Virus.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

AUTHORS CONTRIBUTIONS

Sakshi Wankhede: Conceptualization, Visualization, Editing, Review; Anil Pethe: Visualization, Review.

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