Innovative Reviews in Engineering and Science, ISSN: 3048-8745 Vol. 3, No. 1, 2026 (pp. 9-18)

REVIEW ARTICLE

ECEJOURNALS.IN

A Review of Biodegradable Biomaterials for Medical Device Applications

Luca Arthur[1], Liam Ethan[2*]

[1-2]*Biomechanics Section, Department of Mechanical Engineering, KU Leuven, Leuven, Belgium*

KEYWORDS:
Biodegradable Biomaterials;
Medical Devices;
Biocompatibility;
Tissue Engineering;
Controlled Drug Release;
Sustainable Materials

ARTICLE HISTORY:
Submitted : 11.01.2025
Revised : 23.02.2025
Accepted : 11.03.2025

https://doi.org/10.31838/INES/03.01.02

Abstract

In the past few years, the field of biomedical engineering has made great progress in advancing the development and utilization of biodegradable biomaterials for medical devices. The non degradable alternatives do offer significant advantages such as no long term complications, no secondary surgeries to remove interal implants, less non healed tissue. This comprehensive review surveys the recent developments, existing uses, and potential future applications of biodegradable biomaterials in the design and in use of medical devices. With the emergence of the need for sophisticated biomaterials that can be safely degraded within the body to aid healing, demand for advanced healthcare continues to rise. Biodegradable materials are revolutionizing treatments in many specialties from orthopedic implants to drug delivery systems. And because they can slowly break down and permeate the body at the same time, helping to promote tissue growth and regeneration, they are ideal for a broad range of medical uses. In this article, we delve into the many different types of biodegradable polymers (both natural and synthetic), which are leading the medical device sector. In this post we will chart the landscape of these materials, learning about their unique properties, methods of manufacturing, and how, specifically, they are changing the realm of medicine. We also discuss the challenges encountered in creating these materials and relevant ongoing research towards minimizing existing deficiencies.

Author e-mail: ethanliam@kuleuven.be

How to cite this article: Arthur L, Ethan L. A Review of Biodegradable Biomaterials for Medical Device Applications. Innovative Reviews in Engineering and Science, Vol. 3, No. 1, 2026 (pp. 9-18).

Introductions

This review aims to provide an in depth view of newly developed biodegradable biomaterials, their ability to contribute significantly to improving patient care and medical outcomes. These materials are utilizing their ability to magnetically respond to touch, use in and provide for enhancements to tissue engineering scaffolds, as well as smart drug delivery systems aimed at making more effective, patient friendly treatment options.

Medical Applications of Natural Biodegradable Polymers

The medical field has been interested in natural biodegradable polymers because they have the properties that are inherently biocompatible and can reproduce the extracellular matrix. Medical Device Application of these materials, based on renewable resources is a wide range and provides many advantages.

Alginate-Based Biomaterials

Recently, alginate, a polysaccharide of brown seaweed has proved to be a viable biomaterial for use in many medical applications. As a very good tissue engineering and drug delivery system material due to its unique properties like biocompatibility, low toxicity, and ease of gelation, it is. Microsponge scaffolds designed to deliver targeted drugs in the treatment of rheumatoid arthritis are the latest among the recent developments in alginate based biomaterials. These structures represent innovative, controlled release structures that increase therapeutic efficacy with minimal side effects. One of the other promising uses of alginate is in the use for the manufacture of hydrogels in wound healing. Natural polymers such as gelatin have been combined to alginate to produce bioactive dressings which accelerate the healing process as well as promote tissue regeneration.

Chitosan and Its Derivatives

Antimicrobial characteristics and potential to promote wound healing have made chitosan derived from crustacean exoskeletons popular in biomedical applications. Over the past decades, chemical modifications of chitosan and blending with other polymers have been recently studied to improve chitosan functionality. An important advancement lies with the development of thermosensitive chitosan-based hydrogels for musculoskeletal tissue engineering. The smart material consists of these materials, which respond to temperature changes, and will be implanted with these inserted at minimally invasive ways and will autonomously gel creating a hydrogel in the body. But when combined with medicinal plant extracts, chitosan has also been shown promising in the creation of antimicrobial dressings. The composite materials provide excellent protection against bacterial infections with good wound healing properties.

Tissue Engineering using Collagen and Gelatin.

Long ago, collagen and its denatured form, gelatin, have been used in the application of tissue engineering. Their mechanical properties have recently been improved by means of different types of processing and also by combining with synthetic polymers. Other ways included development of electrospun collagen and chitosan nanofibers for peripheral nerve regeneration. Such scaffolds replicate a true extracellular matrix and help nerve cells either adhere or grow, while also supplying the necessary structural support. 3D bioprinting applications have also been tested on gelatin based hydrogels. Through careful tuning of the bioink composition and crosslinking density, bioinks have been created that permit the printing of high cell viability and functional complex tissue constructs.

Synthetic Biodegradable Polymers: Moving Medical Device Design Forward

Synthetic biodegradable polymers are better controlled in material properties and rates of degradation compared to natural polymers. This chapter examines the most recent advances in synthetic polymer development and their usage in medical devices (Figure 1).

Poly(lactic acid) (PLA) and Copolymers of PLA

Because of their excellent biocompatibility and tunable degradation rates, poly(lactic acid) (PLA) and its copolymers are becoming increasingly popular in medical device applications. Mechanical properties, and the functionality (biosafety) of PLA, have been the focus of recent research using various processing techniques and composite formulations. Growth of the 3D printed

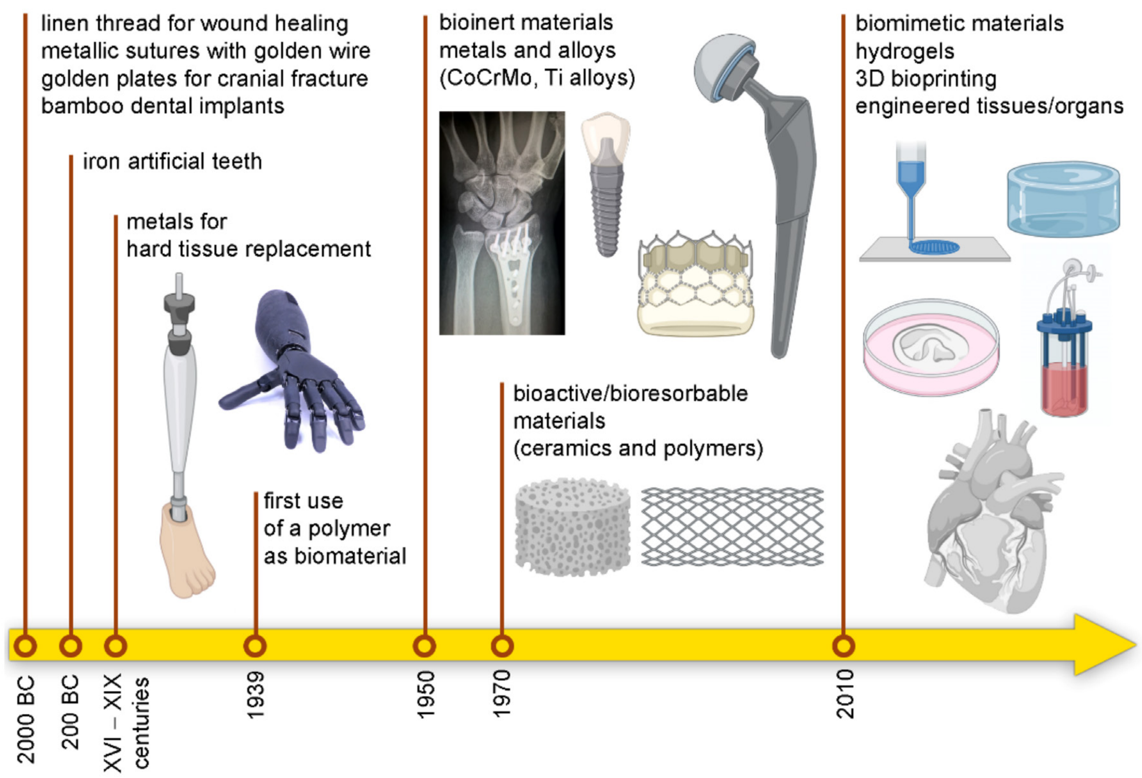

Fig. 1: Chitosan and Its Derivatives

Table 1: Biodegradable Biomaterials for Medical Devices

Biomaterial	Properties
Polylactic Acid	Polylactic acid (PLA) is widely used in medical devices due to its biodegradability, excellent mechanical properties, and suitability for 3D printing.
Polycaprolactone	Polycaprolactone (PCL) is a versatile polymer with good biocompatibility and slow degradation rate, often used for tissue engineering and drug delivery systems.
Chitosan	Chitosan, derived from chitin, is biocompatible, biodegradable, and has antimicrobial properties, making it ideal for wound dressings and tissue scaffolds.
Collagen	Collagen is a natural protein used in medical devices for tissue regeneration and wound healing, due to its compatibility with human tissues.
Silk Protein	Silk protein, known for its biocompatibility and controlled degradation properties, is used in sutures and tissue regeneration applications.
Polyhydroxyalkanoates	Polyhydroxyalkanoates (PHAs) are biodegradable plastics produced by bacteria, with promising applications in medical implants and drug delivery systems.

PLA scaffolds for bone tissue engineering is one of the major advancements. With appropriate control of printing parameters, bioactive agents were incorporated to create porous structures promoting osteogenesis, vascularization. Electrospinning does produce PLA based nanofibers which, on their own, have proven their potential for use in biodegradable vascular grafts. These scaffolds offer mechanical support on the one hand and encourage growth and regeneration of endothelial cells on the other.

Poly(glycolic acid) (PGA), Poly (lactic-co-glycolic acid) (PLGA)

Poly(glycolic acid) (PGA) and its copolymer with PLA (poly (lactic-co-glycolic acid) (PLGA)) have been widely investigated for drug delivery and tissue engineering applications. Recent efforts for improvement in their degradation profiles and their functionality have included surface modifications and composite formulations. Controlled drug release systems using PLGA microspheres have been shown to have great potential for a number of therapeutic applications. Researchers have obtained sustained release profiles from days to months by carefully tuning the polymer composition and processing parameters. PLGA based scaffolds have been successfully used in cartilage regeneration in tissue engineering. Chondrogenic differentiation and matrix production not only depend on the appropriate cells, but also on the presence of bioactive molecules and growth factors.

Polycaprolactone (PCL) and Its Blends

Due to its slow degradation rate and excellent processability, Polycaprolactone (PCL) has recently received considerable attention in medical device applications. There has been recent research in expanding PCL's applications through blending with other polymers with bioactive agents. One example that demonstrates a significant breakthrough is the fabrication of PCL/polyglecaprone composite nanofibers for cartilage tissue engineering. They offer sufficient mechanical support for chondrocyte adhesion as well as chondrocyte proliferation. Additionally, PCL based materials have been shown to be a promising candidates for the biodegradable stents application in the cardiovascular field..

Biomedical Devices Manufactured by Advanced Manufacturing Techniques

However, the ability to develop sophisticated manufacturing techniques has greatly expanded the possibilities for generating novel, complex, functional biodegradable medical devices. This section describes the latest in fabrication techniques and discusses how they affect the design of medical devices.

Additive Manufacturing and 3D printing

However, in recent years, 3D printing has come to modify the production of biodegradable medical devices onto the creation of patient specific implants and scaffolds with complex geometries. Lately, researchers have been chipping away at print resolution, widening printable materials, and adding bioactive agents to the print cycle. Stereolithography (SLA) has been used to create high resolution biodegradable scaffolds for tissue engineering as one important development. This technique provides the ability to control very precisely pore size and distribution, factors critical for supporting cell infiltration and tissue growth. An alternative promising approach is development of multi material 3D printing systems capable of simultaneously depositing diverse biodegradable polymers and bioactive agents. This technology allows the generation of gradient structures and spatially controlled release of growth factors akin to the intricate organization of natural tissues.

Nanofiber Production by Electrospinning

A powerful method for generating nanofibrous scaffolds for which the extracellular matrix can provide useful guidance has emerged in electrospinning. Various efforts have been made, including minimizing fiber misalignment and loading, incorporating bioactive agents, and designing new collectors for 3D structure fabrication. A major advancement is the production of core shell nanofibers via coaxial electrospinning. Compared to other methods, this method allows drugs or growth factors to be encapsulated in the fiber core and readily released over a sustained time course while maintaining the structural integrity of the scaffold. Patterned collectors and additional electrodes are used by researchers to generate aligned nanofiber scaffolds with specified fiber orientation. Laboratory testing of these structures have demonstrated their capability for directing cell growth and inducing tissue regeneration in applications including nerve repair and tendon engineering.

Bioprinting and Cell Laden Constructs

Bioprinting technology promises new routes to engineered cell laden constructs with spatial organization of cells and biomaterials. After these advancements, a major focus has been to refine cell viability in the bioinks and printing parameters to create more complex tissue like structures. An important move is using sacrificial bioinks to incorporate perfusable channels into 3D printed constructs. This concept can then yield vascularized tissue models, overcoming one of the greatest hurdles in the engineering of thick, functional tissues. As another promising approach, in situ bioprinting is developed to apply directly cell laden constructs onto wound sites. It has potential as an approach to speed up the wound healing process and provide greater tissue regeneration in hard-to-heal locations.

Orthopedic Applications of Biodegradable Polymers

The advent of biodegradable polymers has aided greatly orthopedic medicine as a way to provide solutions that promote bone healing while dissolving as new tissue develops. This section covers some of the most recent findings in the use of biodegradable materials for orthopedics.

Bone Fixation Devices

Modern bone fixation devices include biodegradable alternatives to the 'traditional' metal devices. In recent years, these materials have been studied for their mechanical property and degradation profile improvement to more closely conform to bone healing. One such advancement is extending biodegradable polymers with bioactive ceramics to yield composite materials. Hybrid materials made of these improve the osteoconductive and mechanical strength and lead to faster bone regeneration accompanied with sufficient support during the healing. Additionally, surface modifications and drug-eluting coatings have been experimentally studied to increase the performance of biodegradable fixation devices. Thus, these implants can reduce infection risk by including antimicrobial agents or growth factors, and will promote bone healing.

Bone Tissue Engineering Scaffolds

Biodegradable scaffolds offer an important role in bone tissue engineering as temporary structure upon which cells grow and form tissue. It is with these aspects of scaffolds in mind that recent approaches have focused on developing scaffolds with optimized porosity; mechanical properties; and bioactivity, which enhance bone regeneration. An approach that seems to hold promise is the fabrication of gradient scaffolds based on natural bone structure. Researchers have been able to both promote and promote both cortical and trabecular bone formation by carefully controlling the composition and architecture of the scaffold. One area of innovation, in another sense, is the incorporation into biodegradable scaffolds of growth factor or stem cells. Bioactive constructs of these have been found to have enhanced osteogenic potential, leading to faster bone regeneration in critical sized defects.

Cartilage Repair Regeneration

Use of biodegradable polymers has been shown to provide a temporary support structure for chondrocyte growth and matrix production in cartilage tissue engineering. Development of materials which can sustain the mechanical demands within articular cartilage and promote tissue regeneration is the focus of recent research. One interesting new advance has been the ability to make zonal scaffolds that mimic the layered structure of native cartilage. Constructs were developed that promote the formation of cartilage with depth dependent properties by carefully controlling the composition and properties of each layer. Other applications in cartilage repair have also been shown for hydrogel based systems. Some recent studies have looked to the design of injectable in situ forming hydrogels that can be delivered minimally invasively into a cartilage defect matching the shape of the defect (Table 2).

Table 2: Advantages and Limitations of Biodegradable Biomaterials in Medical Devices

Advantage	Benefit
Biocompatibility	Biocompatibility ensures that biodegradable biomaterials integrate well with the human body, minimizing immune rejection and promoting tissue healing.
Controlled Degradation	Controlled degradation allows for the biomaterials to break down at a predetermined rate, making them ideal for applications like drug delivery and tissue scaffolding.
Reduced Inflammatory Response	Reduced inflammatory response is achieved by using natural and biocompatible materials, which help in minimizing irritation and promoting faster healing.
Customizability	Customizability of biodegradable biomaterials allows them to be tailored for specific medical applications, such as creating patient-specific implants or wound dressings.
Sustainability	Sustainability is enhanced as biodegradable materials reduce the environmental impact of medical waste, offering eco-friendly alternatives to traditional plastics and metals.
Reduced Risk of Infection	Reduced risk of infection is associated with the use of materials with antimicrobial properties, such as chitosan, that help prevent bacterial growth in medical devices.

Cardiovascular Applications of Biodegradable Materials

Biodegradable materials have been embraced by cardiovascular medicine for creation of temporary support structures and drug delivery systems. In this section, the latest advances in biodegradable cardiovascular devices and the potential contribution of these new devices to patient care are discussed.

Biodegradable Stents

The biodegradable stent developed as another potential solution in healing vessels by providing temporary support in the diseased vessels until the vessel heals, with the stent gradually disappearing over time. However, recent research has investigated the degradation kinetics and mechanical properties of these devices in order to match the natural healing process of blood vessels. The prefermenting of drug eluting biodegradable stents that can release anti inflammatory and anti proliferative agents locally into the vessel wall are one of the significant advancements. These smart devices allow localized drug delivery then degradation, which presents less risk of late stage complications brought on by permanent stents. In addition, researchers have investigated the formation of hybrid stents, consisting of bioresorbable metals - such as magnesium alloys - and biodegradable polymers, having better mechanical properties than pure polymeric stents and more controlled degradation rates.

Vesels: Vascular Grafts and Tissue Engineeered Blood Vessels

Recent biodegradable materials have displayed much promise for the generation of vascular grafts and tissue engineered blood vessels. Recently there has been a great focus on increasing the development of scaffolds that lead to successful endothelialization and smooth muscle cell growth with adequate mechanical support. The use of electrospun nanofiber scaffolds composed of biodegradable polymers blends shows great promise. These structures duplicate the natural extracellular matrix of blood vessels for cell adhesion and proliferation, and support gradual remodeling into functional tissue. One area of innovation is the development of multi layered vascular grafts that emulate the complex architecture of native blood vessels. Researchers have produced constructs by carefully tailoring compositions and properties of each layer to match those of natural vessels as closely as possible.

Contemporary Myocardial Regeneration and Cardiac Patches

New cardiac patches designed for myocardial repair and regeneration using biodegradable materials have had promise. Together recently, we and other groups have sought to add to the repertoire of scaffolds that encourage cardiomyocyte growth and function as well as angiogenesis and electrical coupling. An important recent development is the engineering of electrically conductive biodegradable scaffolds for cardiac tissue engineering. The electrical coupling between transplanted cells and host tissue is stimulated by these materials, which can contain conductive polymers or nanoparticles. Deployable cardiac patches made from shape memory biodegradable polymers have been studied by researchers as well. These smart materials can be given minimally invasively and expand to blanket had areas of the heart, and provide mechanical support and promote tissue regeneration.

Drug Delivery Systems based on Biodegradable Polymers

Drug delivery systems based on biodegradable polymers have revolutionized the ability of drugs to be delivered

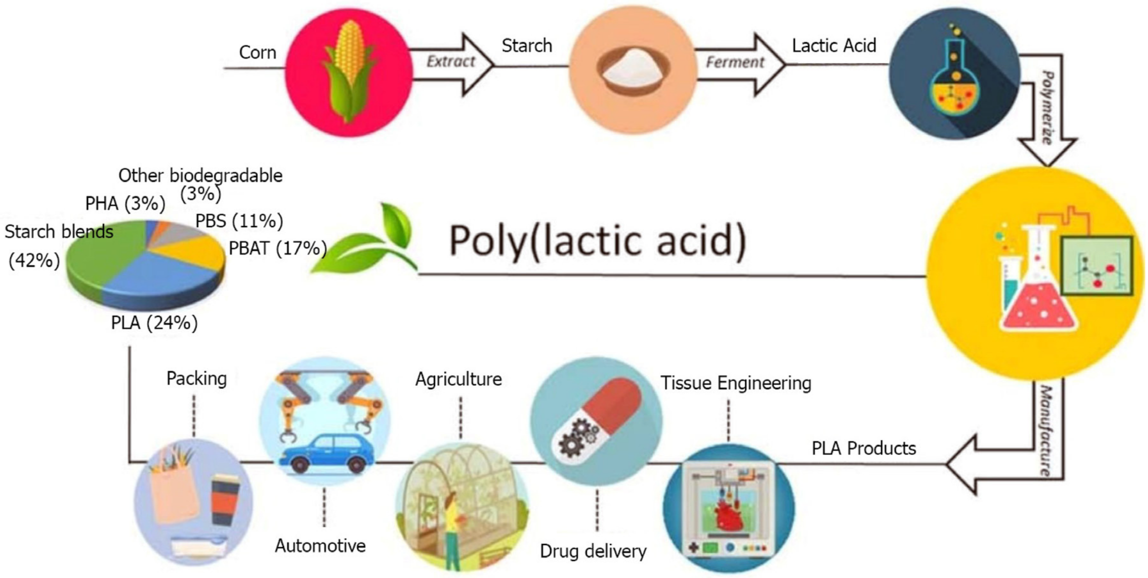

Fig. 2: Drug Delivery Systems based on Biodegradable Polymers

to disease sites in a controlled manner. The last section explores the newest advances in biodegradable drug delivery platforms, looking also at how the development of such systems may affect therapeutic outcome (Figure 2).

Drug Delivery Using Nanoparticles

Recent emergence has made biodegradable nanoparticles into versatile carriers for drug delivery due to enhanced bioavailability and targeted delivery features. The work in recent years has also been devoted to a more rational optimization of the particle size, surface properties and degradation kinetics with the aim of improving the drug loading and its release profile. There has been one major advancement in the development of stimuli responsive biodegradable nanoparticles that allow release of their payload based on selective environmental cues. These smart systems represent on demand drug release to improve therapeutic efficacy and minimize side effects. Other variant projects of recent interest in researchers is the use of biodegradable nanoparticles for co-delivery of multiple therapeutic agents. With the design of the nanoparticle structure and composition paying close attention to the synergistic effects, the mechanism(s) of drug resistance can be overcome.

Implantable Device for Drug Delivery

Biodegradable implantable drug delivery devices also provide the advantage of sustained, localized drug release with removal surgery.And the best and the right chances of migrating them of the possession. Recently the development of devices with tunable release profiles and greater biocompatibility have been the focus of improvements. Therefore one promising approach is through the use of 3D printed biodegradable implants with internal complex anatomy. These structures enable the control of drug release kinetics with high precision and can be tailored to satisfy specific therapeutic requirements. The other area of innovation is the fabrication of biodegradable microchip devices for pulsatile drug release. Most sophisticated systems can simultaneously store and release multiple drugs with preprogrammed manner, enabling the development of new chronotherapy and personalized medicine.

Drug Delivery Systems based on Hydrogels

These hydrogels have proven to be very versatile platforms for drug delivery due to the high water content and tunable properties. Due to recent research, smart hydrogels which react to a wide range of stimuli for controlled drug release have been engineered. Of the notable advancements, self healing, biodegradable hydrogels are created that can resist degradation under physiological conditions. The durability of these materials is greatly improved such that sustained drug release properties are demonstrated for applications requiring long term therapeutics. In an other field, researchers have explored using in situ forming hydrogels for use in minimally invasive drug delivery. In this way, they may be injected as liquids and become gels under physiological conditions providing an easy means of local drug delivery.

Wound Healing and Skin Regeneration: Biodegradable Materials

Advancements in biodegradable materials in wound care have to a great extent revolutionized the field with greater healing outcomes and less scarring. The development of biodegradable wound dressings and skin substitutes, the focus of this section, is explored.

Advanced Wound Dressings

Wound dressings that have evolved to be biodegradable are no longer just a shield around the wound, but also have become active promoters of the healing process. In recent years, we have seen a focus on developing multifunctional dressings that can fix more than one aspect of wound healing at a time. A major achievement is garnering production of nanofiber dressings with incorporated antimicrobial agents. These materials present as a barrier to infections yet encourage cell migration and healing of tissue. Leveraging this approach, another promising direction is to design hydrogel dressings which can respond to the wound environment to promote wound healing. Smart materials, on the other hand, can be reacted by these factors, such as enzyme levels or pH, such that the dispensing of these materials optimizes the healing process.

Tissue Engineered Skin and Skin Substitutes

Biodegradable materials are essential for the development of advanced skin substitutes and tissue engineered skin constructs. Curiously, recent developments in creating multi-layered structures that more or less mimic the complexity of natural skin have only really come to light. Among the important developments is the creation of skin equivalents by 3D bioprinting with appropriate organization in space of different cell types and extra cellular matrix components. By taking this approach it provides more physiological relevant skin models for research and clinical uses. It has also been explored by researchers these are the integration of stem cells and growth factors into degradable scaffolds to promote skin regeneration. Promising results have been reported in regard to these bioactive constructs to accelerate wound closure and minimize the formation of scars.

Prevention and Management of Scar.

Investigation into the use of biodegradable materials in novel approaches for scar prevention and management is a field with a promising future. Recent research has been looking at materials to modulate the wound healing process so the excess scar formation is minimized. An ad vance is made that loading anti-florotic agents into electrospun nanofiber scaffolds presents a promising approach. When provided as these kinds of materials, they can deliver drugs that may inhibit excess collagen production and encourage tissue remodeling in a more organized fashion while still providing mechanical support to the wound. The technological innovation here is the creation of biodegradable membranes for surgical use to prevent post operative adhesions. These barriers can separate healing tissues, allow less fibrous connective tissue formation, and improve surgical outcome..

Applications of Biodegradable Polymers in Neurosurgery

Biodegradable materials have been adopted by the field of neurosurgery for various applications, e.g., nerve repair, to drug delivery in the central nervous system. In this section, the development of biodegradable neurosurgical devices and their potential for improving patient care is explored.

Nerve Guidance Conduits

Promotion of peripheral nerve regeneration has been demonstrated with biodegradable nerve guidance conduits. With special attention given to biotechnological applications for nerve conduits, much recent research has focused on the creation of conduits with optimized microstructures and bioactive properties for facilitating nerve growth and functional recovery. Towards such an advancement it has been possible to create multi-channeled conduits that can guide the growth of individual nerve fascicles. Dorner et al. found these structures as directional cues to reconstructing the axons and improve the accuracy of reconnection. Supportive cells and growth factors have also been incorporated into biodegradable conduits by researchers. Enhanced regenerative potential has been shown of these bioactive constructs, specifically in large nerve gaps.

Dural Substitutes

Traditional neurosurgical applications with non-degradable materials have advantages over biodegradable dural substitutes. In recent years, efforts have been made to develop materials that can impart a watertight seal while also encouraging natural dura mater growth. In particular, use of electrospun nanofiber as dural membranes is a promising approach. These materials possess good handling properties, which allow easy suturing, and provide a porous structure to facilitate cell infiltration and tissue integration. In situ forming hydrogels for dural repair are another area of innovation. These materials can dissolve as liquids and harden to form a solid barrier under physiological conditions, providing a convenient barrier for hard to reach areas.

Application to Drug Delivery to the Central Nervous System

Novel drug delivery systems for the central nervous system were developed using biodegradable materials. In recent research, we have attempted to create platforms that can get past the blood brain barrier and deliver sustained localized drug release. Notable advancement is the development of biodegradable nanoparticles that can cross blood brain barrier. By engineering these carriers to target specific cell types or regions of the brain, they provide new opportunities for treating neurological disorders. Using biodegradable implants to introduce localized drug delivery in the brain has also been considered by researchers. During neurosurgical procedures, these devices can be placed to deliver sustained release of therapeutic agents, to potentially improve outcome in brain tumor or epilepsy.

Future Perspectives and Challenges.

With the field of biodegradable biomaterials on the rise there are some very promising prospects as well as some big challenges. The future directions of research and development in this evolving field are explored in this section. Even more advanced and functional materials are in the future of biodegradable biomaterials. New polymer chemistries and composite formulations for new composites are being explored by researchers to make composites with superior properties and functionality. Another area of interest involves development of shape memory biodegradable polymers responsive to a particular stimulus and able to shape change. Smart materials such as these could completely change the face of minimally invasive surgical techniques and the possibility of creating self deploying medical devices. Another emerging technology is 4D printing, which uses 4D printing to create biodegradable, shape changing or function changing structures. But this could form the basis for more adaptive implants that adapt and evolve while healing the body.

Clinical Translation and Regulatory Considerations

There is significant challenge in regulatory navigation and successful clinical translation as new biodegradable materials and devices are developed. Because of the novel nature of these materials new testing and approval processes need to be established and researchers and companies have to work closely with regulatory bodies. An important realm of research aims to standardize the testing methods for testing the long term safety and effectiveness of biodegradable implants. It involves assessing the degradation products and their possible impact on adjacent tissues. Another very important consideration is the scalability, and manufacturability of new biodegradable devices. For widespread clinical adoption to occur, it will be key that consistency of quality and performance be assured across large scale production.

Conclusion

The development of personalised medicine is thus intimately linked to the advancement of biodegradable biomaterials. Researchers are exploring how to make patient specific devices that can be customized to a patient's unique needs and biology. Among the 3D printing technologies that are emerging as promising approaches is the generation of custom implants from patient imaging data. That could mean more precise and therefore effective treatments, especially in difficult anatomical areas. An area of innovation is the development of biodegradable scaffolds which can be seeded with a patient's own cells and then implanted. However, this approach may increase the integration and functionality of tissue engineered constructs. The presentation ends with a note that field of biodegradable biomaterials for medical device applications is a rapidly moving field and appears poised to deliver exciting possibilities for improving patient care and treatment outcomes. A variety of challenges related to biodegradable medical devices are well within the realm of research and development and we can anticipate new projects leading to more sophisticated and effective devices in the years to come.

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