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"PCL Based Coating for 3D Printed Biodegradable Implants: A Review"

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ABSTRACT: Poly(caprolactone) (PCL)-based coatings on 3D-printed biodegradable implants present significant potential for advancing regenerative medicine and drug delivery systems. PCL, an FDA-approved biodegradable polymer, offers excellent biocompatibility, flexibility, and customizable degradation rates, making it ideal for diverse biomedical applications such as bone regeneration, cardiovascular therapies, ocular drug delivery, and tissue engineering. This review emphasizes PCL's unique properties and its role in enhancing implant functionality. PCL-coated implants enable controlled and sustained drug release, minimize post-surgical complications, and provide improved mechanical strength and stability. The adaptability of PCL allows for tailored therapeutic solutions, ensuring compatibility with various clinical needs. Advances in additive manufacturing technologies, including Fused Deposition Modelling (FDM) and extrusion-based bioprinting, facilitate precise customization of implants, further enhancing their biomedical utility. Key applications include PCL's use in promoting bone growth, serving as a scaffold for vascular grafts, and delivering localized therapies for ocular and orthopaedic conditions. However, challenges such as limited mechanical strength and optimization of degradation rates remain. Innovative strategies, including the incorporation of smart materials and hybrid systems, hold promise for addressing these limitations.

INDEX TERMS - Polycaprolactone, 3D printing, biodegradable implants, coating, drug delivery, tissue engineering.

1. INTRODUCTION:

Implantable sedate conveyance gadgets offer numerous points of interest counting progressed understanding compliance and diminished side impacts, among others. These are accomplished by keeping up a helpful concentration over a delayed time outline, without the require for visit tablets or infusions. They can be utilized for a wide assortment of clinical applications counting women's wellbeing, oncology, visual malady, torment administration, irresistible infection, and central apprehensive framework disarranges. The larger part of embed gadgets are polymeric poles planned to be embedded subcutaneously or intramuscularly, and the foremost common strategy of addition is through a needle or by surgical implantation. This will be generally traumatic for the quiet in comparison to verbal medicate conveyance. Be that as it may, the long-term sedate conveyance and changes in understanding compliance that this route of conveyance offers may exceed this impediment. This may be especially vital in inveterate conditions where destitute understanding compliance could be a challenge, for illustration in human immunodeficiency virus (HIV) or mental wellbeing condition. Improvement of a gadget made totally from biodegradable polymers may outwit this issue, as the gadget would biodegrade actually to make items that can be excreted effectively by the body once the gadget has accomplished its impact, in spite of the fact that still advertising the plausibility of early expulsion on the off chance that antagonistic impacts required it [1]. Three-dimensional printing may be a handle of building 3D objects from a advanced record. In this handle, a advanced 3D protest is planned utilizing computer supported plan (CAD) computer program. SolidWorks, AutoCAD, and ZBrush are a few illustrations of well known CAD computer program utilized commercially in businesses. Blender, FreeCAD, Meshmixer, and SketchUp are some examples of the freeware commonly utilized to create 3D models. These 3D objects are spared in a

3D printer-readable record arrange. The foremost common widespread record designs utilized for 3D printing are STL (stereolithography) and VRML (virtual reality modeling dialect). [2]. PCL is biodegradable polyesters, and these incorporate polymers such as polyglycolic corrosive (PGA), poly-L lactide (PLLA) and their copolymers. It could be a semicrystalline polymer due to its customary structure, and its softening temperature is over body temperature (59-640 C), but its Tg is -600 C, so within the body the semi crystalline structure of PCL comes about in tall sturdiness, since the undefined spaces are within the rubbery state. PCL was utilized as a bio degradable bundling fabric because it can be de evaluated by microorganisms. Most the biodegradable polyesters appear slower debasement rates than common biopolymers. The disintegration rate of Nano-fiber networks made from these materials takes after the arrange PGA>PLGA>PLLA > PCL [3].

2. MECHANISM OF 3D PRINTING:

i. **Fused Deposition Modeling [FDM]**
A thermoplastic material is melted and laid on the build platform in the layer-by-layer fashion, until the object is formed. Material used are acrylonitrile butadiene styrene [ABS], Poly lactic acid [PLA], nylon [4].

ii. **Bio-printing**
Biological material are extruded through the nozzle under pressure to lay down material in the sequential layers till the scaffolds is built. Material used are alginate, chitosan, gelatin, collagen, and fibrin [5].

iii. **Selective Laser Sintering [SLS]**
A high power laser beam fuses the powdered material in the layer-by-layer pattern to form an object. Material used are nylon, polyamide.

iv. **Continuous Liquid Interface Production [CLIP]**
CLIP is similar to SLS expect for the UV beam is passed through a transparent window at the bottom of the resin and built platform raises upward holding the 3D printed object. Material used is photopolymer [6].

v. **Electron Beam Manufacturing [EMB]**
EMB is similar to SLS, expect for high power electron beam is used to fuse the powdered particles. Material used are titanium, cobalt-chrome alloy.

vi. **Stereo-lithography [SLA]**
Each layer is solidified and built on the top of next until the object is formed. A UV laser beam selectively hardens the photo-polymer resin in layer. Material used is photopolymer [7].

vii. **Inkjet/ Binder Jetting**
A liquid binding material is selectively dropped into the powder bed in alternative layer of powder-binding liquid-powder, until the final object is formed. Material used are starch or gypsum (powder bed) and water (binding agent) [8].

viii. **Polyjet**
Polyjet printing is similar to inkjet, but instead of binding agent, photopolymer liquid is sprayed in layer onto the build platform and is instantaneously cured using UV light. Material used are polypropylene, polystyrene, polycarbonate.

ix. **Laminated Object Manufacturing [LOM]**
Layer of adhesive coated material are successively glued together and cut in required shape using laser. Material used are thin sheet of paper, polyvinyl caprolactam [PVC] plastic or metal laminate.

Table 1: Applications of 3D printing

Sr.no	Sector	Application
1.	Industry	Jigs, fixture, and end use parts for aeronautical industry, prototype and spare parts for automotive industry.
2.	Medical	Surgical model for perioperative surgical preparations, dental fixture, bridge and crowns, customized patient implants and prostheses, living tissue scaffolds for tissue engineering and regenerative medicine.
3.	Pharmaceutical	Customized implants for drug delivery, tables, capsule and other patient specific dosages.
4.	Food	Designing and 3D printing complex shaped cake, cookies, candies, pizzas and other desserts.
5.	Fashion	Jewelry, clothes, shoes and it is also applicable in other accessories.

Table 2: Biomaterials classification with their advantages, disadvantages, and applications [9, 10]

Sr.no	Types	Example	Advantages	Disadvantages	Application
1.	Metal and metal alloy	Gold, platinum, titanium steel, chromium, cobalt.	- High material strength. - Easy to fabricateand sterilize.	- Corrosive - Aseptic loosening - Excessive elastic modulus	Orthopedic implants, screws, pins and plates.
2.	Polymer	PMMA, Polycaprolactyane, PLA, polycarbonates, polyurethanes	- Biodegradable - Biocampatiable - Easily moldable and readily available. - Suitable mechanical strength.	- Hard to sterile. - Leachable in body fluid. - Excessive elastic modules.	- Orthopedic and dental impalnts. - Tissue engineering scaffolds. - Drug delivery system.
3.	Composites	Dental filling composites.	-Excellent mechanical property. - Corrosive resistant.	- Expensive - Laborious manufacturing methods	- Dental filling - Rubber catheters and gloves.
4.	Ceramics and carbon compounds	Calcium phosphate salts (HA), glass.	- High material strength. - Biocompatible	- Difficult to mold.	- Bioactive orthopedic implants.

2.1 Limitation of 3D printing

In spite of the fact that 3D printing has the capacity to manufacture on-demand, exceedingly personalized complex plans at moo costs, this technology's therapeutic applications are constrained due to need of differing qualities in biomaterials. Indeed with the accessibility of assortment of biomaterials counting metals, ceramics, polymers, and composites, restorative 3D printing is still kept by variables such as biomaterial printability, appropriate mechanical quality, biodegradation, and biocompatible properties. As a rule, in expulsion based bioprinting, higher concentrations of polymers are utilized in manufacturing bioinks to get auxiliary keenness of the conclusion item. This thick hydrogel environment limits the cellular arrange and useful integration of the framework. For any direct measured natural platform to be utilitarian, vascularization is of utmost significance, and isn't conceivable with the current 3Dprinting technology. Little scale platforms as of now printed within the research facilities of analysts can effortlessly survive through dissemination, but a life-size utilitarian organ must have a lavish vascularization. To address this issue, consolidation of conciliatory materials amid the framework manufacture has been utilized by numerous analysts. These materials fill up the void spaces, giving mechanical back to the printing materials, and once develops are created, they are evacuated by post-processing strategies. Numerous sacrificial/fugitive materials counting carbohydrate glass [11].

Also, plan initiated impediments cause fabric discontinuity, due to destitute change of complex CAD plan into machine informational. Handle initiated impediments incorporate contrasts in porosities of CAD protest and wrapped up 3D printed item [12].

3. USES OF PCL BASED COATING BIODEGRADABLE IMPLANTS:

1. Bone Regeneration

Biodegradable implants are gaining interest for healing bone deformities because they can naturally break down in the body and have properties that support bone repair. Bone is a living tissue that helps with movement, protects organs, and can break (fracture). Materials used to fix bones need to support new bone growth, not interfere with healing, and should break down in the body over time. Biodegradable implants meet these needs because they help bone grow, don't cause harm, and naturally degrade in the body. This makes them a promising option for bone repair [13].

2. Spinal Fracture Intervention

Biodegradable implants, like screws, rods, plates, and cages, are made from different polymers. Studies on animals and humans reviewed their effectiveness and safety in treating spinal fractures [14].

3. Cardiovascular diseases

Cardiovascular disease is now the top cause of death, and stents are commonly used to treat it. Biodegradable polymer stents have gained attention because they break down naturally after helping arteries heal. Unlike non-biodegradable stents, these dissolve over time, leaving behind healthy, regenerated arteries, making them a promising option for treating heart diseases [15].

4. Ocular Delivery

Treating eye disorders with medications can be challenging because the drugs often don't work well in the eyes, may affect other areas of the body, can have side effects, and patients might not follow their treatment plans. While injections directly into the eye can improve drug delivery, they require frequent repeats and can cause side effects from the injections themselves. To address these issues, researchers have developed biodegradable implants that release drugs slowly over time. This helps deliver the medication more effectively to the eyes without needing constant injections, making treatment easier and safer [16].

5. Used as a burr-hole cover in neurosurgery

Osteoplug™ is a polycaprolactone (PCL)-based implant designed as a burr-hole cover used in neurosurgery. It is biocompatible, biodegradable, and designed to promote bone regeneration while gradually resorbing over time. Osteoplug™ provides structural support and reduces complications such as infections or unsightly depressions that may occur after cranial surgeries. Additionally, its 3D-printed structure ensures a precise fit, contributing to improved patient outcomes. [17].

4. SYNTHESIS OF PCL:

Polycaprolactone (PCL) is a biodegradable polyester that's commonly used in biomedical applications because it's compatible with the body and breaks down naturally over time. To make PCL, the main approach is ring-opening polymerization (ROP), where a monomer called ε-caprolactone is opened up and joined together to form long chains of PCL. Various catalysts are used to control the ROP process, including metals like aluminum and tin, because they help create PCL with high molecular weight (how long the polymer chains are) and a low polydispersity index (how uniform the chain lengths are). This method is preferred because it produces a consistent, high-quality PCL. There are also other methods like radical polymerization and enzymatic synthesis, but these are less commonly used for high-quality PCL. E-Caprolactone (epsilon-caprolactone) is an organic compound that serves as the monomer (building block) for creating polycaprolactone (PCL). It's a cyclic ester (also known as a lactone) with a six-membered ring structure. In the presence of specific catalysts, ε-caprolactone can undergo ring-opening polymerization (ROP), where the ring opens up and the molecules link together, forming long chains of PCL. Due to its chemical structure, ε-caprolactone is highly reactive and ideal for creating biodegradable polymers, making it useful in producing PCL for medical and environmental applications.

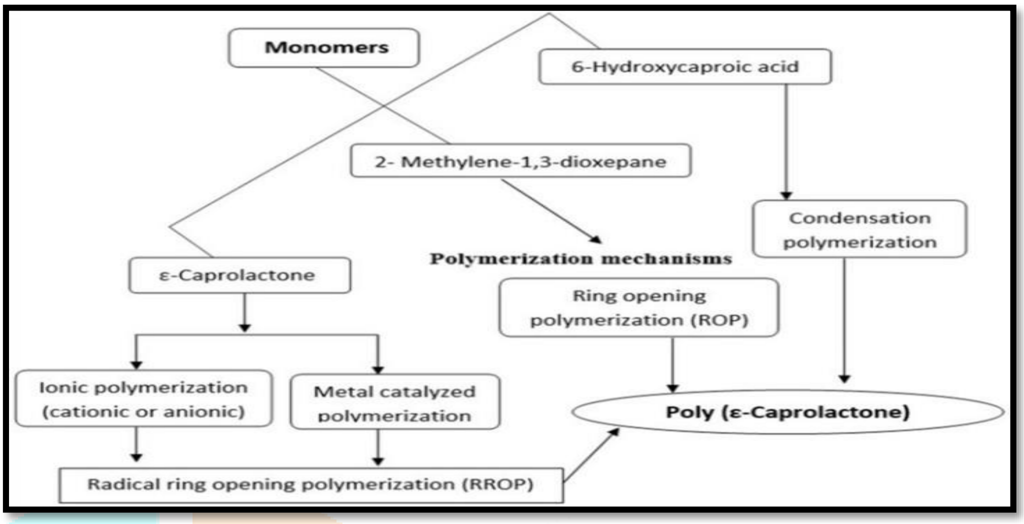

Fig. 1. Synthesis of PCL [18].

4.1. Application of PCL

1. Vascular Craft

Artificial blood vessels, such as those made from polytetrafluoroethylene (ePTFE), are widely used. Polycaprolactone (PCL) is a key material in creating small-diameter blood vessel scaffolds through electro spinning. PCL scaffolds promote faster healing, endothelialization, and integration with the body, making them promising for artificial blood vessels.

2. Bone

Polycaprolactone (PCL) is a key material used for these scaffolds. It is often combined with osteoconductivity ceramics like forsterite, calcium alginate, hydroxyapatite, magnesium phosphate, bioactive glass microspheres, and tricalcium phosphate, which promote bone growth. PCL can also be blended with natural materials like silk fibroin to support bone repair and regeneration. These combinations create an optimal environment for bone cell growth and healing.

3. Other Application

Most related to tissue engineering, taking advantage of the longer times of degradation which can be decreased to adjust to the new tissue formation rate: cartilage, liver, bladder, skin, nerve [19].

5. CONCLUSION:

In conclusion, poly (caprolactone) (PCL)-based coatings offer significant potential for enhancing the functionality and performance of 3D-printed biodegradable implants. PCL's unique properties, such as biocompatibility, biodegradability, and mechanical strength, make it an ideal candidate for developing coatings that can be used in a variety of biomedical applications. The versatility of PCL allows for customization in degradation rates and mechanical properties, making it suitable for implants used in different tissues and therapeutic contexts. Moreover, PCL-based coatings can serve as carriers for bioactive agents, enabling localized drug delivery, improved tissue integration, and reduced post-surgical complications. Further research is required to optimize these factors and expand the use of PCL in more complex medical scenarios, such as multi-layered coatings or the incorporation of other biodegradable materials to improve performance. Future directions may also involve integrating PCL with smart technologies for responsive, on-demand therapeutic delivery. Overall, PCL-based coatings for 3D-printed biodegradable implants represent a promising advancement in the field of regenerative medicine and drug delivery systems. Their ability to provide both structural support and therapeutic functionality ensures that they will continue to play a crucial role in the development of next-generation medical implants, offering patients more effective and personalized treatment options.

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