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Three dimensional printing techniques and their applications in medicine

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Abstract

The beginnings of 3D printing are estimated to date back to 1984. Since then, the technology has evolved significantly thanks to the development of software and a significant increase in computer power. 3D technology is used in many areas of orthopedic medicine. From the production of bone models, implants and the creation of drugs. Thanks to the development of software and biological materials, it is possible to create personalized patient implants or create much more accurate models than using single MRI or CT images in order to better plan the treatment procedure. Currently, materials made of paper, metal, ceramics and hydroxyapatite are used. Unfortunately, the above technology has a number of disadvantages. Despite continuous development, the costs are often several times higher than when using traditional therapeutic methods. Additionally, the amount of materials that can be used is limited. Perhaps this will change in the future, because the technology itself offers promising possibilities that may allow for much more accurate, personalized treatment and faster recovery of patients.

Purpose

This study provides a comprehensive review of the most commonly used 3D printing techniques in medicine, with particular emphasis on the medical fields in which these methods are most frequently applied and where technological development is advancing most rapidly

Materials and Methods

A review of current literature was conducted, focusing on the most popular 3d imprinting methods which could be use in medicine. Most common and frequent methods were evaluated and explained. Literature available in the PubMed and Google Scholar databases was searched using keywords.

Results

The most commonly used techniques include IJP, FDM, SLS, and SLA. Numerous variants of these techniques are currently employed in the production of pharmaceuticals, surgical models, and surgical implants. Despite their significant potential, major limitations remain, particularly high costs and the limited availability of suitable materials. Nevertheless, this rapidly evolving field at the intersection of technology and medicine is expected to enable significantly more efficient medical procedures in the future

Key words: 3D imprinting, medicine, innovations, medicaments

1. Introduction

The beginning of 3D printing is considered to be 1984, when the SLA stereolithography technique was invented by Chuck Hull, which he then patented in 1986 [1]. This gave rise to further improvements and one example of this is its modified FDM fused deposition technique, created in 1988 by Scott Crump. Since then, many methods have been developed and they are used in newer and newer fields. Other techniques used are SLS, BDJ, TIP, PAM[2,3]. They differ in cost, precision, materials used and required equipment, which translates into different applications. One of the fields in which 3D printing has begun to be used is medicine. Examples of fields of medicine in which 3D printing is used are orthopedics, cardiology, maxillofacial surgery, dentistry, and rehabilitation [3], but 3D printing has also been used with great success in the production of medicines [1]. The process itself requires preparation and combination of knowledge from many branches of science. It is necessary to apply knowledge in the field of biomaterials that will be appropriately adapted to a given case. Ceramic, polymer, metal, composite or tissue materials are used the most often [4]. In addition, knowledge of programming and designing spatial models is needed. Most often, models are made using CAD software based on computed tomography and magnetic resonance imaging. After appropriate development and processing of the image, we obtain a model that can be used for printing. The printed model must then undergo final processing and preparation for use[5].

2. **Examples of three dimensional imprinting methods**

2.1 Inkjet Printing (IJP)

Inkjet printing (IJP) is a material deposition method based on the controlled application of liquid materials in the form of microscopic droplets. The droplets are generated using thermal, electromagnetic, or piezoelectric actuators, following precisely programmed digital instructions. The size and frequency of the droplets can be adjusted by modifying parameters such as temperature, actuator pulse frequency, and material properties, which allows for high-resolution and highly controlled fabrication processes. Due to its exceptional precision, IJP is considered one of the most promising techniques in biomedical applications, particularly in tissue engineering and regenerative medicine. The method enables the deposition of bioinks composed of cells, biomaterials, and growth factors with minimal mechanical stress, which is crucial for maintaining cell viability. As a result, inkjet printing has been extensively investigated for the fabrication of simple tissue constructs, such as skin layers, vascular structures, and cartilage-like tissues. Although the printing of fully functional organs remains at an experimental stage, ongoing research demonstrates the significant potential of this technology in the future of regenerative therapies. In addition to tissue engineering, IJP is also applied in pharmaceutical manufacturing. The ability to precisely control droplet size and deposition patterns allows for accurate dosing of active pharmaceutical ingredients, making inkjet printing suitable for personalized drug delivery systems and the production of complex dosage forms with controlled release profiles.

2.2 Fused Deposition Modeling (FDM)

Fused deposition modeling (FDM) is one of the most widely used and cost-effective 3D printing techniques. Its operating principle is analogous to that of inkjet printing; however, instead of liquid droplets, FDM utilizes a continuous filament of thermoplastic material. The material is heated above its melting temperature and extruded through a nozzle, which deposits it layer by layer according to a predefined digital model. Once deposited, the material cools and solidifies, forming a three-dimensional structure. The popularity of FDM results from its relatively low equipment and material costs, ease of use, and wide availability of printable thermoplastics. Despite offering lower resolution compared to some other additive manufacturing techniques, FDM provides sufficient accuracy for many medical applications. In particular, it has been widely explored for the fabrication of anatomical models, such as bone fracture replicas, which can be used for preoperative planning and surgical education [6,7]. Furthermore, FDM has found practical applications in orthopedics, including the production of patient-specific immobilization devices. Personalized casts and splints for forearm fractures fabricated using FDM technology offer improved comfort, ventilation, and hygiene compared to conventional plaster casts [8]. Although limitations related to surface finish and material biocompatibility persist, ongoing developments in filament materials continue to expand the clinical applicability of FDM.

2.3 Selective Laser Sintering (SLS)

Selective laser sintering (SLS) is an additive manufacturing technique based on the fusion of powdered materials using a high-energy laser beam. The process involves spreading thin layers of powder—typically composed of polymers, ceramics, or metals—across a build platform. The laser selectively sinters or melts the powder particles according to the digital model, bonding them together layer by layer to form a solid structure.

One of the primary advantages of SLS is its ability to produce complex geometries with high mechanical strength and excellent structural integrity. The level of detail achievable with this method is largely dependent on the precision of the laser system and the physical properties of the powder material. In medical applications, SLS has been investigated for the fabrication of implants, scaffolds for bone tissue engineering, and drug delivery systems.

However, the use of high temperatures during the sintering process raises concerns regarding the thermal degradation of heat-sensitive active pharmaceutical ingredients, which limits the applicability of SLS in pharmaceutical manufacturing. Despite these challenges, experimental studies have explored the use of SLS for producing porous bone scaffolds that support cell adhesion and tissue regeneration, demonstrating its potential in transplant medicine [9]. Nevertheless, the high cost of equipment and operational complexity restrict the widespread adoption of SLS in clinical settings.

2.4 Stereolithography (SLA)

Stereolithography (SLA) is an additive manufacturing technique that utilizes liquid photopolymer resins with photosensitive properties. The printing process involves selectively curing the resin using ultraviolet (UV) light, which induces polymerization and solidification in predefined regions. By repeating this process layer by layer, highly detailed three-dimensional objects can be produced. SLA is renowned for its exceptional resolution, smooth surface finish, and ability to fabricate intricate geometries, making it particularly suitable for applications requiring high precision. In medicine, SLA is commonly used for producing dental models, surgical guides, hearing aid shells, and anatomical models for surgical planning. The main limitations of this technique include the relatively high cost of materials and concerns related to the long-term biocompatibility and mechanical stability of photopolymer resins.

2.5 Digital Light Processing (DLP)

Digital Light Processing (DLP) is a vat photopolymerization technique similar to stereolithography (SLA), but instead of using a laser to selectively cure the resin, it utilizes a digital light projector to expose entire layers of photosensitive resin simultaneously. This approach significantly increases printing speed while maintaining high resolution and surface quality. In medical applications, DLP is frequently used for the production of dental prostheses, surgical guides, and hearing aids, where fine details and smooth surfaces are critical. The technology also shows potential in fabricating microfluidic devices for drug testing and organ-on-a-chip systems, which require complex, highly detailed geometries. One advantage of DLP over SLA is the shorter printing time for large or complex models, although material limitations and post-processing requirements remain similar [1,2].

2.6 Electron Beam Melting (EBM)

Electron Beam Melting (EBM) is a powder bed fusion technique that uses a high-energy electron beam to selectively melt metal powders, layer by layer. This method allows for the production of dense, high-strength metallic components, making it particularly suitable for orthopedic and dental implants that require excellent mechanical properties. EBM is often employed to produce titanium-based implants with complex lattice structures that promote osseointegration and reduce implant weight. The high-energy electron beam allows for rapid melting and solidification of metal powders, resulting in fully dense parts with mechanical characteristics comparable to wrought metals. While EBM offers advantages over conventional manufacturing, its limitations include high equipment cost, need for vacuum conditions, and the necessity of specialized training to operate safely [3,4].

2.7 Laminated Object Manufacturing (LOM)

Laminated Object Manufacturing (LOM) is an additive technique in which thin sheets of material—such as paper, plastic, or metal laminates—are bonded together using heat, pressure, or adhesives, and then cut into the desired shape using a laser or knife according to digital instructions. Layer stacking forms a three-dimensional object.

Although LOM provides lower resolution compared to SLA or DLP, it offers a cost-effective method for producing large-scale anatomical models, surgical simulations, and educational tools. LOM models are particularly advantageous when visualizing complex structures such as organs or skeletal systems because multiple colors and textures can be incorporated to distinguish anatomical features. Despite limited use in direct clinical applications, LOM remains valuable for medical education and preoperative planning.

2.8 Continuous Liquid Interface Production (CLIP)

Continuous Liquid Interface Production (CLIP) represents an emergent photopolymerization technique. It employs a continuous ultraviolet light source and an oxygen-permeable window to sustain a liquid interface, thereby facilitating rapid, layerless polymerization. This approach dramatically increases printing speed while preserving high resolution and mechanical fidelity. CLIP has demonstrated potential in producing biocompatible, high-precision components for dental restorations, hearing aids, and prosthetic devices. In regenerative medicine, research is ongoing to adapt CLIP for printing soft tissue scaffolds and flexible implants. Although still in early stages of clinical application, CLIP represents a promising advancement in rapid, high-resolution 3D printing technologies

2.9 Binder Jetting (BJ)

Binder Jetting is an additive manufacturing process in which a liquid binding agent is selectively deposited onto a powder bed, layer by layer, to create a solid object. After printing, the part is typically cured or sintered to improve mechanical strength. Binder jetting is versatile in terms of material use, including ceramics, metals, and polymers, and is valued for its speed and ability to create full-color models. In medicine, binder jetting is often used to produce anatomical models for surgical planning and patient education. It is also being explored for creating bone scaffolds, dental prostheses, and drug formulations where porosity or gradient structures are required. However, the method generally produces parts with lower mechanical strength compared to SLS or EBM, limiting its use for load-bearing implants

2.10 Extrusion-Based Bioprinting

While FDM is primarily used with thermoplastics, extrusion-based bioprinting is a specialized technique in which cell-laden bioinks are extruded through fine nozzles to create living tissue constructs. This method allows for the deposition of multiple cell types and biomaterials simultaneously, enabling the fabrication of heterogeneous tissues such as cartilage, vascularized skin, and liver-like structures. Extrusion-based bioprinting has become a cornerstone of tissue engineering research. It offers excellent control over cell density and spatial distribution, although challenges remain in maintaining cell viability during extrusion and ensuring adequate nutrient and oxygen diffusion in thick tissue constructs. Combined with other methods like IJP and DLP, extrusion-based bioprinting is paving the way toward functional organ fabrication

3. The benefits of 3D printing techniques

The main advantages of 3D technology are reduced surgical procedure time, shortened recovery time and better results for patients after surgery related to the personalized selection of tools for a given patient. The disadvantages, however, are the still high costs of using the technology and the still quite narrow scope of use related to, for example, the limited number of materials that can be effectively used in humans [11]. The operation requires qualified staff, and the process time from the start to the end of production of the finished model may last from several hours to several days[3][12].

The main application of 3D printing is the preparation of anatomical auxiliary models for surgery and training models. Other applications include personalized bone implants or prostheses. In orthopedics, 3D printing is most often used for knee, hip, shoulder and hand surgery. In other fields of surgery, it is often used in maxillofacial, skull, spine and dentistry [3].

SLA technology can be used in bone grafts used to reconstruct bones after accidents or cancer. Promising materials are hydroxyapatite [HA] compounds and beta-tricalcium phosphate (β-TCP). The composites used have a similar structure to bone tissue, and HA compounds facilitate the bonding of the graft to the bone. The disadvantage of these materials is their limited mechanical strength, which is why they are used mainly for small bone defects that do not bear heavy loads [13, 14].

Another new field of application of 3D printing is manufactured implants. There are cases of the use of vertebral implants in cancer diseases requiring surgical removal of the affected vertebra or in chronic spine pain requiring surgical intervention [15]. One example is the case of a patient where a 3D printed implant was successfully used to reconstruct the spine after surgical treatment of Ewing's tumor [16] and fabrication of an arthrodesis implant for a patient with chronic pain in the cervical spine [17]. Successful attempts have been made to produce personalized joint prostheses. Hip sockets, articular surfaces of the tibia, and reconstructions of entire ankle bones are produced [18]

An application that facilitates the performance of procedures is the creation of pre-operative models allowing for planning the operation. In some spine surgeries, models are printed that allow planning the course of nailing insertion into the spine, for example in advanced scoliosis [19,20]. Such models have specially designed and adjusted angles corresponding to the true curvature of the patient's vertebrae. Another example is the design and production of bone models and guides adapted to them in the case of hip dysplasia or fractures in the neck of the femur[21]. As in the case of vertebrae models, here the tools are also adapted to the mapped curvatures of the patient's bones.

4. Fields of medical application of 3D printing

4.1 Anatomical Models and Surgical Planning

One of the most established applications of 3D printing in medicine is the production of patient-specific anatomical models derived from medical imaging data, such as computed tomography (CT) and magnetic resonance imaging (MRI). These models provide a tangible representation of complex anatomical structures, enabling clinicians to better understand pathological conditions and anatomical variations [22,23].In surgical planning, 3D-printed models are particularly valuable in complex procedures, including maxillofacial surgery, neurosurgery, orthopedic surgery, and cardiovascular interventions. Surgeons can use these models to simulate procedures, select optimal surgical approaches, and anticipate potential complications. The use of anatomical models has been shown to reduce operative time, improve surgical accuracy, and enhance clinical outcomes [23]. Additionally, such models facilitate effective communication between healthcare professionals and patients.

4.2 Medical Implants and Prothesis

Additive manufacturing has significantly advanced the design and production of medical implants and prosthetic devices. Conventional manufacturing techniques often rely on standardized implant dimensions, which may not adequately reflect patient-specific anatomical variability. In contrast, 3D printing allows the fabrication of customized implants with high geometric complexity and precision [24].

In orthopedic applications, 3D-printed implants are used for bone reconstruction, spinal implants, and joint replacement components. The ability to produce porous structures promotes osseointegration and improves long-term implant stability. In dentistry, 3D printing is widely applied in the manufacture of dental implants, crowns, bridges, orthodontic appliances, and surgical guides [25,26,]. Moreover, customized limb prostheses produced via additive manufacturing offer reduced production time, lower cost, and improved patient comfort.

4.3 Pharmaceutical Applications of 3D Printing

The pharmaceutical industry has increasingly investigated the use of 3D printing for drug formulation and personalized therapy. This technology enables precise control over drug dosage, geometry, and release characteristics, allowing medications to be tailored to individual patient requirements [26].

One notable application is the development of polypills, which combine multiple active pharmaceutical ingredients into a single dosage form. This approach has the potential to improve patient compliance, particularly in chronic disease management. The approval of the first 3D-printed drug by the U.S. Food and Drug Administration demonstrated the feasibility of additive manufacturing in pharmaceutical production [27,29]. However, regulatory challenges and material limitations currently restrict widespread clinical implementation.

4.4 Bioprinting and Tissue Engineering

Bioprinting represents a rapidly developing branch of 3D printing that involves the deposition of bioinks composed of living cells and biomaterials. This technology plays a crucial role in tissue engineering and regenerative medicine [28].

Current research focuses on the fabrication of skin, cartilage, bone, and vascularized tissue constructs. Bioprinted skin has shown promise in wound healing and burn treatment applications. In the future, bioprinting may offer solutions to the shortage of donor organs by enabling the fabrication of functional tissues for transplantation. Nevertheless, challenges related to vascularization, long-term tissue viability, and ethical considerations remain significant [29,30].

4.5 Surgical Instruments and Patient-Specific Guides

3D printing is also used in the production of surgical instruments and patient-specific surgical guides. These guides assist surgeons in accurately positioning instruments during procedures such as orthopedic osteotomies and dental implant placement, thereby increasing procedural precision and reducing intraoperative errors [30,31]. Furthermore, additive manufacturing allows rapid, on-demand production of surgical tools, which is particularly advantageous in emergency situations, remote healthcare settings, and resource-limited environments.

4.6 Medical Education and Training

In medical education, 3D printing is increasingly utilized to produce realistic anatomical models for teaching and training purposes. These models allow students and clinicians to practice surgical techniques and understand complex anatomical relationships without risk to patients [31,32, 33]. Simulation-based training using 3D-printed models has been shown to improve technical skills, procedural confidence, and overall clinical competence, contributing to enhanced patient safety and educational effectiveness.

5. Conclusion

The number of fields of medicine in which 3D printing technology can be used is increasing. This is due to the development of materials that can be successfully used. Increasing access to technology translates into reduced costs of using devices and materials. Improved photo processing software translates directly into shorter procedures and their accuracy. Despite the increasing development and improvement of 3D technology, the costs may still be high, as in the case of SLS techniques. Despite the increasing number of biomaterials available, only a small part of them can be effectively used in humans, for example due to their poor mechanical strength. The technology itself still requires a highly qualified team consisting of doctors, radiologists, and programmers who can process photos and remake the image into a 3D model, which unfortunately leads to increased costs and longer time. Many problems have been dealt with over the last decades. Currently, 3D printing can be successfully used in orthopedics, neurosurgery, pharmacology and veterinary medicine. By creating prostheses, anatomical models, personalized implants, and new forms of drug administration, the treatment of some patients can be improved.

Disclosure

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