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Application of 3D Printing Technology for Medical Purposes: A State of the Art

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Abstract — *Introduction:* The application of 3D printing technology in healthcare has revolutionized various medical practices, allowing for personalized solutions tailored to individual patient needs. This study explores the current state of 3D printing in medical applications, highlighting its benefits and challenges. *Method:* A comprehensive review of existing literature was conducted, focusing on the utilization of 3D printing for creating anatomical models, prosthetics, and bioprinting of living tissues. The analysis included a survey of various additive manufacturing techniques, such as Selective Laser Sintering (SLS) and Stereolithography (SLA), to assess their effectiveness in medical contexts. *Results:* The findings indicate that 3D printing enhances surgical planning by providing accurate anatomical models, thereby improving surgical outcomes. Additionally, the technology facilitates the production of custom implants and prosthetics, leading to better integration with patients' anatomy. Bioprinting has shown promise in developing artificial organs and regenerative therapies, significantly impacting transplant medicine. *Discussion:* While 3D printing offers substantial advantages, challenges such as regulatory hurdles, ethical considerations, and the need for standardized practices remain. The technology's potential in personalized medicine is vast, suggesting a future where individualized treatments are commonplace. Continued research and collaboration among medical professionals, technologists, and regulatory bodies are essential to address these challenges and optimize the benefits of 3D printing in healthcare. This study underscores the transformative impact of 3D printing in medicine and its potential to enhance patient care and outcomes across various applications.

Keywords — Printing; Three-Dimensional; Human; Preventive Medicine; Models; Anatomic

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INTRODUCTION

3D printing technology has brought a significant revolution in various aspects of the health sector. One of the main benefits of 3D printing in a healthcare context is its ability to print anatomical structures of the human body precisely and according to individual needs [1]. Through 3D printing, 3D models of specific organs, bones, or tissues can be created for more accurate surgical planning. It helps doctors visualize the patient's internal body structures before performing complex surgical procedures [2]. In addition to anatomical models, 3D printing enables the creation of individually tailored medical devices, such as implants and prosthetics. By utilizing this technology, medical professionals can design and print implants that match the patient's geometry and anatomical needs, reducing the risk of rejection and increasing surgical procedure success [3]. Likewise, with prosthetics, 3D printing makes it possible to create prosthetics that suit the patient's needs, improving their mobility and quality of life. Recent breakthroughs in 3D printing technology have brought us closer to printing living tissue and human organs. Through 3D printing techniques related to bio-printing, researchers can publish living tissue structures that mimic human body organs. It opens up tremendous opportunities for developing artificial organs for transplantation, regenerative medicine, and drug research [4].

3D printing also plays a vital role in medical education and patient education. 3D models of organs and tissues can be used to train physicians in the planning and execution of surgical procedures, as well as to clarify complex medical concepts. On the other hand, these models can also educate patients about their conditions and planned treatment procedures, increasing patient understanding and involvement in their care [5]. Additionally, 3D printing contributes to developing innovative medical devices, such as customized medical imaging tools and case-specific surgical equipment. 3D printing enables the production of these medical devices at lower costs and faster than traditional methods, accelerating innovation in the healthcare field. Not only that, 3D printing technology is also used in making diagnostic aids, such as models of tumors or other pathological conditions. These models can be used for virtual surgical practice, more precise treatment planning, and patient education about their conditions. It helps improve the accuracy of diagnosis and treatment planning and provides better treatment options for patients. Furthermore, 3D printing is also used to produce rehabilitation and therapy aids, such as customized splints or braces. Through 3D printing, these devices can be precisely manufactured according to patient needs, increasing the effectiveness and comfort of their rehabilitation treatments [6].

In addition, 3D printing also plays a role in drug development and clinical research. 3D models of organs or tissues can be used in clinical trials to test the effectiveness and safety of new drugs, speeding the development of more efficient medicines. In addition to direct applications in the health sector, 3D printing also has the potential to improve health infrastructure in remote or disaster-affected areas [7]. Through 3D printing, medical devices can be produced locally and on demand, reducing dependence on external supplies and speeding response in emergencies. However, although 3D printing has brought many benefits to the health sector, ethical and regulatory challenges still need to be overcome. The availability of this technology may raise questions about patient privacy, product quality, and medical responsibility [8]. Therefore, efforts must be made to ensure that 3D printing in the healthcare sector is used responsibly and by applicable ethical and regulatory standards. This analysis presents an overview of the applications of 3D printing in the medical field, highlighting its uses and limitations as well as its benefits for the development of health sciences.

Additive Manufacturing (Am) Technology

Additive Manufacturing (AM) technology, better known as 3D printing, has brought a revolutionary transformation in the medical field. Using AM, three-dimensional objects can be printed layer by layer based on digital models, resulting in a wide range of individually tailored medical devices [9]. Apart from that, Additive Manufacturing Technology has also presented various types of innovative printing methods in the medical field (Figure 1). First is the Selective Laser Sintering (SLS) technique, where a laser combines material powders, such as metal or polymer, layer by layer to form a three-dimensional object. This method is suitable for manufacturing complex, durable medical devices like bone implants or orthopedic aids. Next is the Stereolithography (SLA) technique, where the photopolymer liquid hardens after exposure to UV light. This process enables the manufacture of medical devices with a high degree of resolution and precise detail, which is suitable for manufacturing anatomical models or small medical devices such as diagnostic aids [10]. Fused Deposition Modeling (FDM/FFF) technology uses a nozzle to melt and deposit thermoplastic materials into thin layers to form objects. This method is often used for printing prototypes or non-sterile medical devices such as braces or splints.

There is also the Electron Beam Melting (EBM) technique, where an electron beam is used to melt metal in a vacuum. This process is suitable for molding solid and durable metals, such as bone implants or scaffold tissue structures, for tissue engineering. Bio-printing technology uses living cells or biomaterials to print the structure of living tissue or organs. This method allows the creation of artificial organs for transplantation or regenerative medicine and the development of disease models for medical research. There is also Continuous Liquid Interface Production (CLIP) technology, where objects are printed from liquid photopolymer resin using a semi-permeable membrane and UV light [11]. This process enables printing objects at high speed and high resolution, which is suitable for making anatomical models or diagnostic aids. Direct Metal Laser Sintering (DMLS) technology uses lasers to fuse metal powders, such as titanium or stainless steel, into three-dimensional objects. This method is suitable for making bone implants or other medical devices that require high strength and durability [12].

Furthermore, Laminated Object Manufacturing (LOM) technology uses layers of materials, such as paper or plastic, that are cut and put together to form a three-dimensional object. This process is suitable for prototyping or medical devices that do not require a high level of resolution. Binder Jetting technology uses powdered materials that are stuck together using a liquid binder to form objects [13]. This method is suitable for making anatomical models or non-sterile medical devices such as braces or splints. Electron Beam Melting (EBM) technology uses an electron beam to melt metal in a vacuum chamber. This process is suitable for molding solid and durable metals, such as bone implants or scaffold tissue structures, for tissue engineering. Next is Inkjet-based 3D Printing technology, where ink or bioactive material is sprayed through a nozzle onto the surface of the support to form a three-dimensional object. This method is suitable for printing live tissue or customized medicines [14].

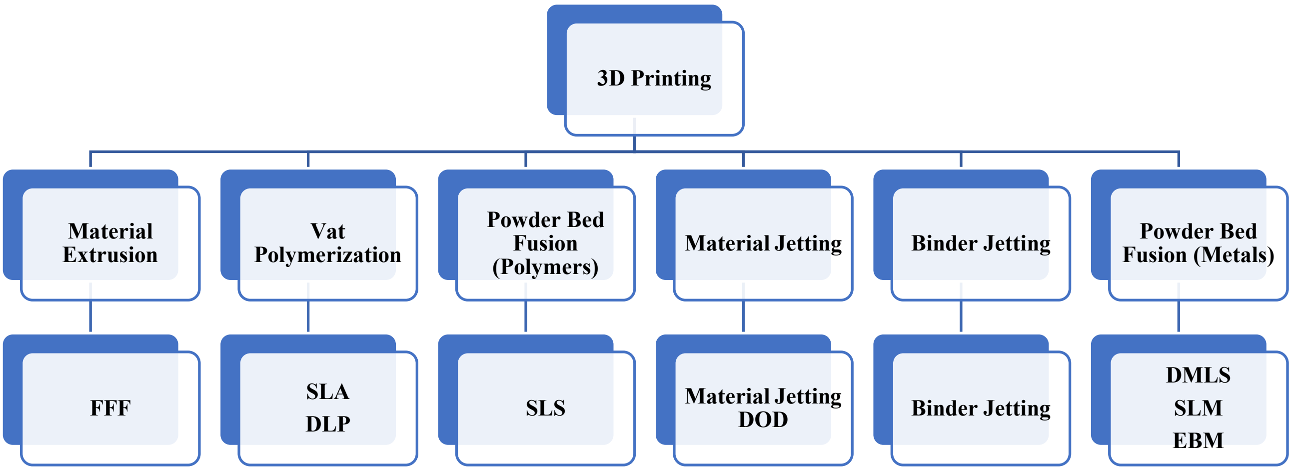

Fig. 1. Additive Manufacturing (AM) technology.

Vat Photopolymerization technology uses a hard photopolymer resin to form three-dimensional objects when exposed to UV light. This process is suitable for manufacturing anatomical models or small medical devices such as diagnostic aids. Next is Material Jetting technology, where liquid or semi-liquid material is sprayed through a nozzle and diluted into a thin layer to form an object [15]. This method is suitable for printing prototypes or medical devices that require high resolution. Powder Bed Fusion technology uses a laser or energy beam to melt and combine powdered materials into three-dimensional objects. This process is suitable for manufacturing complex, durable medical devices, such as bone implants or orthopedic assistive devices. Sheet Lamination technology uses layers of material stuck together to form a three-dimensional object. This method is suitable for making anatomical models or non-sterile medical devices such as braces or splints [16]. Finally, Directed Energy Deposition technology uses a nozzle to melt and deposit metal or plastic powder to form three-dimensional objects. This process is suitable for manufacturing prototypes or medical devices that require high strength and durability. For a comprehensive overview of the advantages and disadvantages of 3D printing, **Table 1**.

Table 1. the advantages and disadvantages of 3D printing

3D Printing	Advantages	Disadvantages
FFF	1. FFF is the first 3D printing technology people are introduced to and represents the largest installed base of 3D printers worldwide. 2. The low cost of materials and machines, as well as ease of use, make FFF a highly competitive method for producing custom thermoplastic parts. 3. FFF is the most popular choice for rapid prototyping and some functional applications, mainly for non-commercial use, due to the wide range of materials available.	1. The primary limitation of FFF stems from the anisotropic nature exhibited by components. 2. FFF's method of layered printing inherently leads to components being weaker in specific orientations. 3. The strength of a component in various orientations is impacted by its positioning during the printing process. 4. The strength of a component is influenced by the percentage of infill. Typically, most printers utilize a 20% infill ratio. Increasing the infill percentage enhances the strength of the part but also extends production time and costs. 5. The layer-by-layer printing approach characteristic of FFF results in visible layer lines on components, often necessitating post-processing for achieving a smooth surface finish.
SLA DLP	1. The main advantages of vat polymerisation are its ability to produce parts with a smooth surface finish and exceptional accuracy and detail. 2. Smooth surface properties make SLA technology particularly suitable for replicating or producing prototypes similar to injection moulded products, making it a preferred choice for 3D printing applications. 3. SLA is often used to produce visual models such as figurines, housings and hand-held consumer products where a polished surface is a key requirement. 4. Vat polymerisation is one of the most precise 3D printing methods and is ideal for producing intricate components that require tight tolerances and detailed features, particularly in sectors such as jewellery and dental care.	1. The primary limitation of SLA printing is the material properties of the photopolymers used, which are inherently brittle and lack the impact resistance and durability of injection moulded components, limiting their usefulness in the production of functional parts. 2. Components produced using SLA/DLP processes typically have a limited-service life due to the gradual degradation of their mechanical properties over time, particularly in sunlight-exposed environments, necessitating the application of coatings to extend their life. 3. The material limitations associated with photopolymers are the main factor behind the limited integration of vat polymerisation technologies into functional applications.
SLS	1. An advantage of the SLS process is that it does not require a substrate. This eliminates the need to remove the support material after printing and ensures a consistent surface finish without the negative effects of the support material interacting with the surface as seen in FFF and SLA printing. 2. Selective Laser Sintering (SLS) excels at producing durable functional parts with intricate geometries. Its isotropic properties and impressive accuracy, while not reaching the levels of vat polymerisation or material	1. The main drawback of SLS printing is its industrial scale, with machines costing around $250,000. Skilled operators and advanced material handling are essential, resulting in longer lead times compared to other 3D printing technologies. 2. The critical heating and cooling phases of SLS printing contribute significantly to longer lead times. This process typically takes around 20-24 hours to print a full 300 x 300 x 300 mm container, followed by an additional 12 hours of cooling before post-processing can begin.

	jetting, often make it the preferred choice for producing end-use components.	3. Modern SLS machines often have the ability to externally heat or cool powder containers, which improves operational efficiency. Despite this, SLS parts typically have a rough, matte surface finish unless they undergo post-processing.
Material Jetting DOD	1. Material Jetting ensures near homogeneity of parts. The layers cure continuously during the printing process. 2. Parts produced by Material Jetting have very smooth surfaces, comparable to injection moulded parts. 3. Material Jetting is recognised as the most dimensionally accurate form of 3D printing, increasing the accuracy of the final part and is the preferred method for producing realistic, non-functional, prototypes that closely represent end-parts.	1. Mechanical limitations Similar to SLA, which uses photopolymers to produce parts, material jetting has significant drawbacks, particularly in the mechanical properties of the resulting parts. These parts often have poor mechanical properties and are inherently brittle. 2. Material jetted parts lack the strength found in processes that offer materials such as nylon or true ABS. The fragility of acrylic-based resins presents challenges, particularly in functional testing scenarios. In addition, the limited heat deflection temperature ranges of these materials can hinder real-world testing and functional applications. 3. Elasticity challenges is when considering rubber-like materials, the lack of elongation can pose problems when testing applications that require elasticity, thereby hindering accurate evaluation. 4. Material Jetting is proving to be one of the most expensive 3D printing methods compared to alternative technologies, largely due to the exorbitant cost of materials. Unlike FFF or SLA, which use low-volume lattice-like support structures, Material Jetting uses full-mass supports, resulting in significant material waste, adding to the already high cost of ownership.
Binder Jetting	1. Binder Jetting's elimination of heat during the process offers a key advantage by reducing the development of residual stresses commonly associated with rapid heating and cooling during part production. 2. The absence of a heat source in Binder Jetting not only reduces the likelihood of residual stresses, but also contributes to lower operating costs, while enabling large parts to be printed, further improving cost effectiveness. 3. Economical binders include low-cost materials such as silica sand for sand cores and moulds used to bind sand or metal powder in binder jetting. Despite the increased costs associated with metal powders in metal printing, binder jetting remains significantly more economical than powder bed fusion, with cost differences of several orders of magnitude.	1. Mechanical fragility, the main limitation of binder jetting relates to the mechanical properties of the parts, as parts directly from the print bed are particularly fragile. 2. Requirement for secondary processing, a secondary process is always essential if functionality is required from a Binder Jetted part, adding an extra step to the manufacturing process. 3. Grainy surface finish, parts produced by binder jetting often have a grainy surface finish due to the inherent nature of the process.

	4. Significantly larger parts can be produced with binder jetting.	
DMLS SLM EBM	1. Complex parts is DMLS/SLM excels at producing complex and bespoke components that require a high degree of customisation. 2. Unique Geometries, it can produce geometries that traditional manufacturing methods cannot achieve. 3. The process is particularly effective for topology optimisation to reduce weight, especially in aerospace and automotive applications. 4. DMLS/SLM is well suited to creating the organic shapes that are essential in medical and dental applications. 5. Parts are produced from proven metal materials, providing predictable and reliable performance.	1. The high cost of metal 3D printers and the materials they use makes DMLS/SLM less economical for certain applications, such as the production of generic washers, fasteners or large parts. 2. Build size, the largest metal 3D printers have limited build volumes compared to conventional manufacturing methods, limiting the size of parts that can be produced. 3. The successful production of metal parts requires a thorough understanding of the design principles that are specific to 3D printing.

3D Bioprinting

3D bioprinting is an innovation that changes the paradigm in the medical world by enabling the printing of living tissue structures or organs using living cells or biomaterials as "ink." This technology opens the door to a new era in healthcare, enabling the creation of complex structures that mimic the structure and function of human organs. One of the main advantages of 3D bioprinting is its ability to print tissue structures with high precision and detail. Using this technology, researchers can design and print tissue structures that suit a patient's specific needs, helping to reduce the risk of rejection and increasing organ transplants' success [17]. 3D bioprinting also opens up tremendous opportunities for developing artificial organs for transplantation. Researchers are using this technology to print living tissue structures that can be used as replacements for damaged or deformed organs, helping to overcome the problem of donor organ shortages and increasing patient recovery rates. Apart from organ transplants, 3D bioprinting is also used to develop regenerative therapies. Researchers are using this technology to print living tissue structures that can stimulate new tissue growth in patients' bodies, speed wound healing, and restore the function of damaged organs [18].

In pharmaceutical research, 3D bioprinting has also made significant contributions. Researchers can use printed living tissue models to test the effects of drugs on specific organs or tissues, speeding up the development of new drugs and increasing their success rates. Not only that, 3D bioprinting also opens up new opportunities for creating disease models for medical research. Researchers can print living tissue structures that mimic certain disease conditions, such as cancer or diabetes, to study the mechanisms of those diseases and develop more effective therapies. However, 3D bioprinting technology faces several challenges, including difficulties in printing complex and vascular tissue structures [19]. Safety and ethical issues are also a concern, including the risk of rejection and the long-term effects of using artificial tissue in the human body. Despite this, the development of 3D bioprinting technology continues, with research ongoing to overcome these challenges and increase its effectiveness in medical applications. In the future, 3D bioprinting will become an essential part of modern medical care, bringing significant benefits to patients needing organ transplants, regenerative therapies, and drug research [20].

PROCESS AND MATERIALS USED IN MEDICAL 3D PRINTING

Image Acquisition

Image acquisition is an essential first step in the 3D printing process for medical applications. This step involves taking pictures or scanning the internal structures of the patient's body using medical imaging technology such as computed tomography (CT) scan, magnetic resonance imaging (MRI), or ultrasound. CT scan technology allows detailed imaging of a patient's internal body structures with high resolution, while MRI offers a more detailed view of soft tissues. Meanwhile, ultrasound is generally used for real-time imaging and monitoring progress directly. The quality of the image obtained is crucial to producing a 3D model that is accurate and appropriate to the patient's anatomy. Once the image has been obtained, the next step is data processing. This process involves converting image data into a format that can be used for 3D printing. It can include image segmentation to identify specific structures and organs, noise removal, and other processing to improve data quality. Special software is used to process image data into three-dimensional models that can be printed. Data processing is a critical stage in the creation of accurate 3D models [21]. A deep understanding of medical imaging technology and data processing is required to ensure that the resulting models meet clinical needs. Attention to small details and optimizing parameters to produce a high-quality model is essential. In addition, data integrity and patient privacy are also significant concerns at this stage. Protecting sensitive medical data is a priority in medical image capture, storage, and processing. Robust security systems and compliance with data privacy standards are necessary to protect patient medical information. Advances in medical imaging technology continue to drive the capabilities of 3D printing in medical applications. Advanced, high-quality medical imaging enables the creation of more precise and detailed 3D models, which can be used for better surgical planning, manufacturing customized medical devices, and better understanding of a patient's clinical condition. Thus, image acquisition is a crucial step in facilitating the development of 3D printing technology for more advanced medical applications [19].

Segmentation

Segmentation is an essential process in 3D printing for medical applications that involves identifying and separating specific structures or organs from medical image data. The main goal of segmentation is to separate areas of the image or imaging data related to the structure to be reconstructed in a 3D model. In medicine, segmentation is necessary to isolate specific organs, tissues, or areas from CT, MRI, or other medical imaging images. Radiologists can carry out this process manually or automatically using special software that implements segmentation algorithms. Manual segmentation allows a high degree of control over the results, as the radiologist can adapt the segmentation process to the patient's specific needs. However, this method requires significant time and human effort and is prone to human error. On the other hand, automatic segmentation uses computer algorithms to process image data and identify specific structures automatically. However, faster and more efficient automatic segmentation may only sometimes produce optimal results, especially in complex cases or imperfect images [22].

The results of the segmentation process are the basis for creating accurate 3D models. Good segmentation is vital to ensuring that the resulting model accurately reflects the patient's anatomy. In addition, segmentation also makes it possible to isolate specific areas to be studied or operated on, allowing better planning and more precise interventions. Although segmentation is critical in 3D printing for medical applications, challenges remain in ensuring segmentation accuracy and consistency, especially in complex cases or imperfect images. Therefore, developing more advanced and automated segmentation techniques is ongoing to improve the quality and efficiency of this process, with the ultimate goal of improving clinical and patient outcomes. Overall, segmentation plays a vital role in 3D printing for medical applications by enabling the identification of relevant structures from medical image data and forming the basis for the creation of 3D models that are accurate and appropriate to the patient's clinical needs. By continuing to develop more advanced segmentation techniques, we can accelerate and increase the efficiency of using 3D printing in medicine and patient care [23].

File Optimization for Final Print

File optimization in the context of 3D printing for medical applications is a process that involves optimizing a 3D model before printing it. The main goal is to increase printing efficiency, minimize material use, improve print quality, and reduce production time. One commonly used technique in file optimization is polygon reduction, where the number of polygons in a 3D model is reduced without sacrificing the quality of the geometry. It can reduce printing time and memory required, as well as increase the speed and accuracy of the printing process. In addition to polygon reduction, file optimization can involve surface meshing, optimizing die orientation, and efficient arrangement of support structures. Surface blending eliminates creases and small gaps between polygons, resulting in a smoother, easier-to-print surface. Orientation optimization involves optimally placing the 3D model on the printing platform to reduce the required support and optimize print quality [24].

Buffer setup is also vital for file optimization in medical 3D printing. Stands are needed to support parts of the model that float or tend to collapse during the printing process. By structuring the supports efficiently, we can reduce the material used and minimize the possibility of mold defects. It is essential for printing complex, small-sized medical structures, where print accuracy and strength are critical. File optimization in medical 3D printing significantly improves the printing process's efficiency, quality, and reliability. We can increase productivity and reduce overall costs by reducing the amount of material used in production time and the possibility of defects. Additionally, better and more accurate print results enable the development of more advanced medical devices and better meet patient needs. It is essential to continue to develop more advanced file optimization techniques and algorithms to meet the increasingly complex and diverse needs of medical 3D printing. By implementing the right file optimization strategies, we can maximize the potential of 3D printing technology in improving patient care and advancing the healthcare field [25].

Three-Dimensional Printer and Material Selection

3D printing technology has significantly changed the processes and materials used in manufacturing medical devices. One transformational aspect is the ability of 3D printing to use a wide range of materials, from metals to bio-compatible materials. It enables the creation of more complex and diverse medical devices tailored to patient needs and specific medical applications. 3D printing also makes it possible to manufacture medical devices with more complex designs and higher precision. In contrast to traditional manufacturing methods that require cutting, casting, or machining processes, 3D printing makes it possible to create products layer by layer based on a pre-designed digital model. It results in a more precise product that meets the desired specifications. 3D printing also allows the creation of medical devices that are individually tailored according to the patient's anatomical needs. Medical experts can design and print medical devices that fit the patient's body structure by using medical imaging scanning technology, such as MRI or CT scans. It helps reduce the risk of rejection and increases the effectiveness of medical treatment. In addition, material transformation has also enabled the development of new materials suitable for medical applications. For example, there is the development of bio-compatible materials that can be used to print living tissue structures or human organs. These materials enable the creation of artificial organs for transplantation or regenerative medicine [26].

The processes and materials used in 3D printing also enable the development of lighter, more robust, and more durable medical devices. For example, bone implants made from new materials in the orthopedics industry can create better solutions for patients with injuries or bone conditions. In addition, process transformation also enables the development of more affordable and mass-available medical devices. By using fast and efficient 3D printing methods, manufacturers can produce medical devices at lower costs and in less time than traditional methods. 3D printing also enables faster and cheaper prototyping of medical devices. It allows developers to test the design and function of medical devices before entering mass production, saving product development time and costs. The transformation of processes and materials in 3D printing also enables developing more innovative and adaptive medical devices. Medical experts can design devices tailored to individual patient needs, allowing for more personalized and effective treatment. In addition, material transformation also allows the creation of more environmentally friendly medical devices. New materials that are recyclable or made from natural sources help reduce the carbon footprint and environmental waste produced by the medical industry [27].

The transformation of processes and materials in 3D printing has also opened up new opportunities in medical research and drug development. Researchers can use this technology to print anatomical models of the human body or artificial organs for clinical trials, speeding the development of more effective and safer medicines. In addition to direct applications in medical devices, the transformation of processes and materials in 3D printing also impacts other areas of the medical industry. It includes the development of diagnostic aids, surgical tools, portable medical devices, and more. However, as with every new technology, there are challenges to overcome when using 3D printing in the medical field. It includes regulatory issues, safety, and quality standards that must be adhered to to ensure the safety and effectiveness of medical devices manufactured using this technology [28].

Print (Validation and Quality Control)

The printing process in 3D printing for medical applications requires strict validation and quality control to ensure that the printed objects comply with established standards. Validation begins by checking the suitability of the digital model to the object to be printed. It involves design verification to ensure the digital model accurately reflects the intended anatomical structure and other specifications. After design validation, the printing process begins, and throughout this process, quality control is continuously carried out to monitor the print results. A critical aspect of quality control in medical 3D printing is the dimensional aspect. It involves measuring the dimensions of the printed object to ensure that the size and proportions are as desired. This measurement can be done using a dimensional measuring tool or special software that can digitally measure objects' dimensions. Precise dimensions are essential to ensure the accuracy and suitability of the object to clinical needs [29].

Apart from dimensions, quality control also pays attention to the surface quality of the printed object. A smooth, defect-free surface is critical, especially for medical applications where surface smoothness may affect interactions with biological tissue or other medical devices. Visual inspection and surface analysis with special software can be used to evaluate the surface quality of objects. Validation and quality control also involve testing the functionality of printed objects. It is done to ensure that the object can meet its functional requirements, such as strength, stiffness, and resistance to certain pressure or stress. Mechanical and load testing are often performed to measure an object's functional performance and ensure its suitability to clinical needs. The entire validation and quality control process in 3D printing for medical applications is vital to ensure the resulting objects' safety, accuracy, and quality. By carrying out this process carefully, medical professionals can ensure that printed objects meet established standards and can be used effectively in patient care or other medical procedures [30].

DISCUSSION

The 3D printing technology has opened doors for significant transformations in the field of medicine. This innovation allows for the creation of physical objects based on pre-designed digital models, providing tremendous benefits for diagnosis, surgical planning, assistive device production, and even body replacement. Here are some future benefits of 3D printing technology in medicine:

Custom Medical Assistive Devices

Custom Medical Assistive Devices using 3D printing technology is an innovation that allows the creation of medical devices tailored to the specific needs of patients. This technology allows the design of medical aids that can be adjusted according to the patient's body shape, size, and functional needs, such as prosthetics, orthotics, or hearing aids. By using digital scans of the patient's body, these devices can be manufactured with high precision, increasing comfort and effectiveness in their use. The main advantage of using 3D printing in the manufacture of medical devices is the flexibility in design and production [31]. This technology allows for faster and more affordable production compared to traditional manufacturing methods, which often require longer times and higher costs. In addition, 3D printing also supports the use of various materials, from plastic to metal or a mixture of both, which can be adjusted to the medical needs of each device. This provides the flexibility to produce devices that are not only functional, but also lightweight and durable [32]. In a medical context, this technology is very useful for patients with special needs, for example patients with deformities or amputees who require unique prosthetics, or people with mobility problems who need personalized assistive devices. With Custom Medical Assistive Devices based on 3D printing, the quality of life of patients can be significantly improved, because they get the right solution, comfortable, and according to their physical needs. In the future, this technology is predicted to develop further and play an important role in the field of more personalized and effective healthcare [33].

Medical Implants and Artificial Bones

Medical Implants and Artificial Bones using 3D printing technology is an innovation that allows the manufacture of implants and artificial bones that are more precise and tailored to patient needs. This technology uses digital scans such as CT scans or MRIs to create a 3D model of damaged bones or body structures. Based on this model, implants or artificial bones can be printed accurately using biocompatible materials, such as titanium or special polymers, which are safe for use in the human body [34]. The main advantage of using 3D printing in the manufacture of medical implants is its ability to create complex and unique structures that cannot be produced using conventional methods. Implants or bones printed with 3D can be designed to fit the patient's specific anatomy, ensuring perfect adaptation in the body and reducing the risk of complications or implant rejection. In addition, the production process of these implants is also faster and more efficient, so it can speed up the patient's healing time [35]. The use of 3D printing in the manufacture of implants and artificial bones also has a major impact on improving clinical outcomes. With strong and biocompatible materials, these implants can mimic the mechanical properties of real bones, help tissue regeneration, and support bone healing more naturally. This technology paves the way for more advanced, minimally invasive surgical procedures, and allows surgeons to plan and execute operations with greater precision. In the future, 3D printing is expected to grow even further, with the potential to create more complex implants and even print living tissue [36].

Bioprinting Technology

Bioprinting technology is a branch of 3D printing that focuses on printing biological structures, such as tissues or organs, using living cells as the “printing material.” The technology works by layering cells in a bioink (a mixture of cells and biomaterials) to form tissues or organs that mimic natural structures in the human body. With this technique, scientists can create more realistic tissue models for medical research, drug development, and, in the future, even artificial organ transplants [37]. A major advantage of bioprinting is its ability to create tissue that is tailored to a patient’s needs, which is particularly useful in the world of personalized medicine. For example, if a patient needs a skin or blood vessel graft, bioprinting technology can print tissue that matches the patient’s biological structure and properties, reducing the risk of rejection. Bioprinting also paves the way for the development of more accurate disease models, allowing researchers to study pathologies in greater depth without having to rely on animal models or tissue from human donors [38]. While bioprinting is still in its infancy, its potential for the future is enormous. The technology is expected to solve the organ shortage crisis for transplantation, by printing fully functional organs, such as livers or kidneys, from the patient's own cells. In the short term, bioprinting could also be used to accelerate pharmaceutical research by creating human tissue that can be used to test drugs more effectively and safely. Further developments in bioprinting could revolutionize healthcare, especially in regenerative medicine and organ transplantation [39].

Patient Treatment and Care

3D printing technology has brought significant changes to patient treatment and care, especially in terms of personalizing care. One of the main benefits of this technology is its ability to create medical devices, implants, or prosthetics that are tailored to each patient's unique anatomy. For example, doctors can create a physical model of a patient's organs or bone structure using medical scans such as CT scans. With this model, doctors can better plan surgical procedures, reduce the risk of errors, and speed up the patient's recovery. In addition, 3D printing allows for faster and more affordable production of assistive devices and implants [40]. For example, patients who require prosthetics can receive individually designed devices at a lower cost than traditional methods. Medical devices such as splints, braces, and mobility aids can also be manufactured with high precision, increasing comfort and effectiveness for patients. In some cases, 3D printing is even being used to create replicas of a patient's tumor, helping doctors understand the location and structure of the tumor before performing surgery. The use of 3D printing in patient care is also supporting innovations in the field of bioprinting, where artificial biological tissues can be used in regenerative treatments. In the long term, this technology has the potential to print fully functional human tissue or organs for transplantation [41]. This would solve the problem of organ donor shortages and minimize the risk of rejection by the patient's body, since the printed organ can be made from the patient's own cells. This technology continues to develop and promises more personalized, efficient, and effective care for patients in the future.

Public Health Education

3D printing technology plays a significant role in public health education, especially in enhancing visual and interactive understanding for medical professionals and the general public. One of the biggest benefits is its ability to print physical models of organs, tissues, or other anatomical structures in very precise detail. With these 3D models, health educators can provide more realistic and easy-to-understand demonstrations, helping medical students and the public better visualize medical conditions, operations, or disease mechanisms [42]. In the context of medical training, 3D models also allow for the simulation of surgical procedures or other medical procedures without having to rely on cadavers or live patients. This provides a safer and more efficient learning environment, where aspiring health professionals can practice their skills before performing real-life procedures on patients. In addition, this technology is very useful in educating patients about their diseases or health conditions. Doctors can use models of affected organs or body parts to directly explain to patients how the disease progresses or how treatment procedures will be carried out [43]. At the community level, 3D printing also plays a significant role in health awareness campaigns and public education. With the ability to print replicas of viruses, bacteria, or other structures, health organizations can provide more visual and interactive information about a variety of health issues, such as infectious diseases, hygiene, and nutrition. 3D replicas used in public health exhibitions or programs can increase public interest and understanding of the importance of health prevention and care. This technology, with its ability to create lifelike physical models, helps convey complex medical information in a way that is more easily understood by a wider audience.

Accelerated Research and Development

3D printing technology plays a significant role in accelerating the research and development (R&D) process in various fields, especially in the healthcare and technology industries. One of its biggest contributions is its ability to create prototypes quickly and at a lower cost. In the context of medical research, for example, scientists can easily print 3D models of organs, tissues, or medical devices to test new hypotheses or devices before they enter mass production. This saves time in the development cycle, allowing researchers to iterate designs faster and identify potential issues earlier. In addition, 3D printing supports more flexible and innovative experiments. In the pharmaceutical industry, this technology is used to print living tissues that can be used as models for drug trials [37]. These tissues provide a more realistic and ethical alternative to animal testing, while also speeding up the process of evaluating the effectiveness and safety of new drugs. Using this technology, researchers can also print various types of complex molecular structures, which were previously difficult or even impossible to create using conventional methods. This opens up huge opportunities in the exploration of new materials, biomaterials, and molecular design for medical purposes. In the long term, 3D printing has great potential to accelerate developments in regenerative medicine and bioprinting, where artificial tissues or organs can be printed for transplantation or regenerative treatments. This technology allows for the rapid development of more complex and functional tissues, accelerating research into organ regeneration or tissue repair. The impact of this technology is not only accelerating medical innovation, but also accelerating the implementation of new solutions into clinical care, helping to improve the quality of life for patients more quickly and efficiently [39].

Disaster Relief and Remote Healthcare

3D printing technology plays a significant role in disaster relief and remote healthcare, especially with its ability to produce medical devices and emergency supplies quickly and tailored to specific needs. In natural disasters such as earthquakes or floods, access to necessary medical equipment is often limited. With 3D printing, relief teams can print items such as splints, prosthetics, and breathing apparatus directly at the disaster site. This allows for faster and more efficient care to be provided to victims, reducing reliance on outsourced supplies, which may be hampered by road access or logistics. In addition, the technology also supports healthcare in remote, hard-to-reach areas, where medical infrastructure may be inadequate. With a portable 3D printer, medical teams or clinics in remote locations can print critical medical devices, such as surgical equipment, diagnostic instruments, or even prosthetic components [36]. For example, if a patient in a remote area needs a prosthetic or medical device customized to their condition, the device can be manufactured on-site based on digital data, saving time and shipping costs from larger healthcare facilities. This is especially helpful in areas with limited access to medical resources. Furthermore, in disaster scenarios or remote areas, 3D printing supports a just-in-time manufacturing approach, where medical items are printed only when needed. This reduces waste and minimizes the need to maintain large stocks of medical equipment. The technology can also be used to print spare parts for medical equipment that is damaged or disconnected from the supply chain, ensuring that healthcare can continue even during emergencies. With its flexibility and speed, 3D printing is an innovative solution to improve disaster relief response and healthcare in hard-to-reach areas [40].

Organ Transplants and Regenerative Medicine

3D printing technology has a revolutionary role to play in organ transplants and regenerative medicine, with the potential to address the critical shortage of donor organs. One of the most promising applications is the ability to print artificial tissues and organs using the patient's own cells through a process called bioprinting. In this technique, living cells are taken from the patient, cultured, and then printed into a 3D structure that mimics the original tissue or organ. This not only matches the patient's anatomical needs, but also reduces the risk of immunological rejection, since the organ is made from the patient's own biological material. In addition, 3D printing opens up opportunities in the development of regenerative tissues, where support structures or scaffolds can be printed to aid the repair and growth of new tissue [41]. These scaffolds can be made from biomaterials designed to promote the regeneration of cells and blood vessels, thereby accelerating the healing process in cases of tissue injury or degenerative diseases. In the long term, this offers hope for patients with partial organ damage or tissue that cannot be repaired by conventional methods. The technology also allows for the repair of complex tissues such as cartilage, muscle, or blood vessels, which are difficult to regenerate naturally. 3D printing technology in organ transplantation and regenerative medicine is still in the research and development stage, but progress is rapid. Several trials have shown promising results in printing functional tissues such as skin, miniature livers, or heart tissue. With continued innovation, the future of organ transplantation may no longer rely entirely on human donors, but rather on custom-printed artificial organs for each patient. This could drastically reduce waiting times for transplants, increase life expectancy, and provide a solution for many patients who currently do not have access to the care they need [43].

Overall, the future benefits of 3D printing technology in medicine are vast and hold tremendous potential for advancing healthcare, improving patient care, and addressing global health challenges. As the technology continues to evolve and become more accessible, we can expect to see even more groundbreaking applications in the years to come. For example, in 3D printing-based cranioplasty surgery. Cranioplasty is a surgical procedure performed to repair defects or damage to the skull caused by trauma, surgery, or certain medical conditions. One of the latest innovations in cranioplasty is the use of 3D printing technology that allows the creation of more precise skull implants that are tailored to the patient's needs. This technology combines medical imaging capabilities, such as CT scans and MRIs, with additive manufacturing processes to create implants that are close to the natural shape of the patient's skull. With this approach, 3D printing-based cranioplasty provides better aesthetic and functional results than traditional techniques.

The process of creating a 3D printing-based implant begins by taking 3D images of the patient's skull using a CT scan. This data is then processed using engineering software that allows surgeons and medical engineers to design an implant that matches the shape and size of the skull damage. Once the design is approved, the digital file is sent to a 3D printer that will print the implant from biocompatible materials, such as titanium or special polymers that are suitable for use in the human body. The main advantage of 3D printing-based cranioplasty is the ability to produce custom implants. This is especially important because each patient has a unique skull anatomy, and traditional approaches often use “off-the-shelf” implants that may not fully match the patient’s bone structure. With 3D printing, each implant is designed specifically to meet the patient’s needs, improving comfort, aesthetics, and long-term functional outcomes.

In addition, the mechanism of 3D printing cranioplasty surgery also speeds up the process of manufacturing and placing the implant. Compared to conventional methods that require more time to customize the implant to the patient’s needs during surgery, 3D implants are ready to use once printed and shipped. This reduces the surgical time and the risk of complications from longer surgeries. This approach also improves aesthetic outcomes because the implant more accurately mimics the original shape of the skull. Moving forward, 3D printing-based cranioplasty will continue to evolve with the emergence of new material innovations and more sophisticated printing techniques. The use of lighter, more durable materials, as well as printing techniques that allow for the creation of more complex structures, make this technology increasingly important in reconstructive surgery. Ultimately, the combination of modern medical technology and 3D printing-based design may provide better results in repairing skull bone defects, both in terms of aesthetics and functionality for patients.

Fig. 2. The Use of 3D Printing in Cranioplasty Surgery and Prosthetic Manufacturing

CONCLUSION

3D printing technology has a wide and significant role in various medical applications, with the ability to create more precise and personalized medical devices. One of its main applications is the creation of implants and prosthetics that are specifically designed to meet individual needs. In orthopedic surgery, for example, doctors can print bone implants that match the patient's anatomy based on scans such as CT or MRI scans, thereby increasing the success rate of the operation and patient comfort. Prosthetics made with 3D printing can also be customized to the patient's body size and shape, providing a lighter, more comfortable and more functional solution. In addition to implants, 3D printing also plays an important role in surgical planning and medical training. Surgeons can use 3D-printed models of the patient's organs or body parts to plan surgical procedures more accurately. This is especially helpful in complex cases, such as tumors in difficult locations or unusual anatomical structures.

The use of these models allows doctors to simulate before surgery, reducing the risk of complications and reducing the time of surgery. In medical training, 3D models of organs or tissues also help medical students or young doctors practice medical procedures without having to rely on cadavers or live patients. In the future, the medical applications of 3D printing are expected to grow even further, especially with advances in bioprinting, where living tissue and artificial organs can be printed for regenerative medicine. Research is underway to print tissues such as skin, cartilage, and even more complex organs such as livers or kidneys, which could one day be used for transplantation. This technology would not only address the shortage of donor organs, but also allow for more personalized and effective treatments, as printed organs could be made from the patient's own cells, reducing the risk of rejection by the immune system. The medical applications of 3D printing are paving the way for a new era of more precise and efficient healthcare innovation.

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