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# 3D printing technologies in implantable medical devices: principles, applications, and cost-effectiveness in cardiovascular surgery

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## ABSTRACT

Three-dimensional (3D) printing technologies, also known as additive manufacturing, have revolutionized biomedical engineering and surgical applications by enabling the high-accuracy and patient-specific production of complex geometries. Over the past decade, these technologies have moved beyond mere prototype manufacturing into routine clinical and industrial use. This review summarizes the fundamental operating principles, clinical applicability, advantages, and limitations of major 3D printing technologies, including SLA, FDM, selective laser sintering, selective laser melting, and binder jetting. Furthermore, their applications in cardiovascular and cardiac surgery, cost-effectiveness analyses, and future trends are discussed.

**Keywords**: Three-dimensional printing biomaterials, selective laser sintering, stereolithography, selective laser melting, fused deposition modeling, additive manufacturing

## INTRODUCTION

In additive manufacturing (AM), unlike machining methods, the part is produced in layers and production is done by accumulating the required amount of material rather than by subtracting from a block.[1]

3D printing technologies have revolutionized the design and production of medical devices and surgical instruments. The ability to physically reproduce patient-specific anatomical models derived from computed tomography (CT) or magnetic resonance (MR) data provides significant advantages in surgical planning and intraoperative applications. In cardiovascular surgery, where anatomical variation is substantial, these technologies enable precise, patient-specific planning and application.

Initially limited by high costs, material restrictions, and regulatory challenges, 3D printing has become increasingly widespread in hospitals due to advancements in hardware, biocompatible materials, and software.

## PRINCIPLES OF 3D PRINTING PROCEDURE LAYER BY LAYER

The process typically involves:

- Creating a digital model (via CAD or medical imaging data)
- Slicing the model into layers
- Layer-by-layer printing
- Post-processing (cleaning, curing, surface finishing, sterilization)

Each technology uses different physical or chemical mechanisms to form these layers (**Figure 1**).

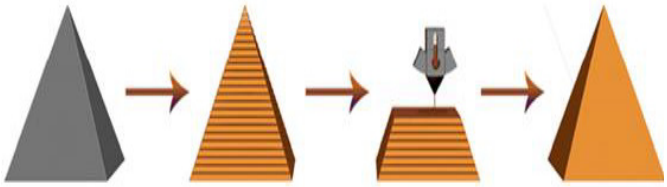

**Figure 1.** 3D printing principle

3D: Three-dimensional

## MAJOR ADDITIVE MANUFACTURING (AM) TECHNIQUES

The materials, advantages, and disadvantages of the techniques are summarized in **Table**.

### Fused Deposition Modeling (FDM)

Invented by Scott Crump in 1988, FDM became the first patented 3D printing technology in 1992 under Stratasys.[2] The principle involves heating a thermoplastic filament (such as polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), polyethylene terephthalate glycol (PETG), or polyether ether ketone (PEEK) to its melting point, then extruding it through a nozzle that deposits the material layer by layer. After each layer solidifies, the platform lowers for the next layer to be added.[3]

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**Table. The advantages and disadvantages of different techniques**

| Methods | Materials | Advantages | Disadvantages |
|---|---|---|---|
| FDM | ABS, PLA, Wax blend, nylon | High speed, high quality, used for a wide range of materials | Porous structure, weak mechanical properties, generally requires support for the binder |
| SLA | Resin (registered photo-curable resin such as acrylic or epoxy-based) | Large parts can be easily produced with high accuracy and surface quality | Use of photo-curable resins, limited mechanical properties, parts need to be post-cured |
| SLS | Metallic powder, polyamide, PVC | High resolution, high strength and durability | Applicable only to metallic and thermoplastic materials, surface roughness requires post-processing |
| 3D inkjet printing | Photo-resin or hydrogel | Very fine detail, high surface quality | Fragile parts, weak mechanical properties |

FDM: Fused deposition modeling, SLA: Stereolithography, SLS: Selective laser sintering, 3D: Three-dimensional, ABS: Acrylonitrile butadiene styrene, PLA: Polylactic acid, PVC: Polyvinyl chloride

- **Advantages:** Low cost, easy operation, wide material range.
- **Disadvantages:** Surface roughness, limited resolution and mechanical strength.
- **Clinical use:** Cardiac anatomical models, preoperative training models.
- **Cost:** Printers between 1,000-10,000 USD; model cost <50 USD.

## Stereolithography (SLA) with Liquid Photopolymer

- **Advantages:** High resolution, smooth surface, ideal for fine details.
- **Disadvantages:** Brittle materials, some resins are not biocompatible.
- **Clinical use:** Surgical guides, molds for silicone vascular or cardiac models.
- **Cost:** Printers 5,000-100,000 USD; resin 150-200 USD/L (**Figure 2**).

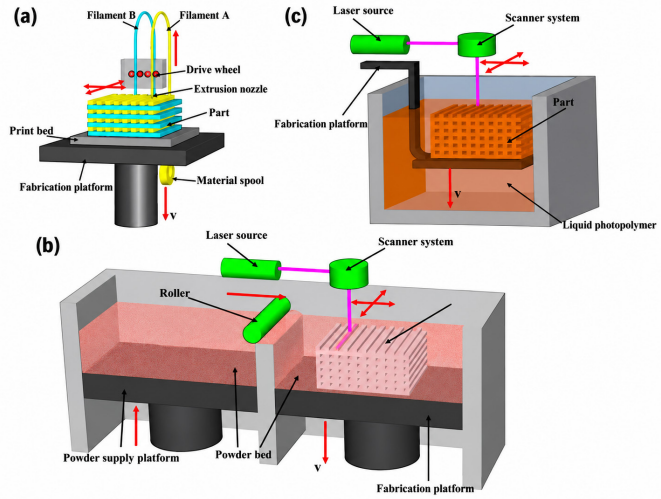


**Figure 2.** SLA uses a laser to polymerize liquid photopolymer resin
SLA: Stereolithography

## Selective Laser Sintering (SLS) with Powder Delivery System

Developed by DTM in 1987 and patented by CR Dechard in 1988, SLS sinters powdered polymers using a laser to partially melt and fuse particles.[4]

- **Advantages:** High strength, no support structures, complex geometries possible.
- **Disadvantages:** Surface roughness, powder cleaning difficulty, high equipment cost.
- **Clinical use:** Vascular connectors, cannula housings, device casings.
- **Cost:** 100,000-500,000 USD; reduced per-unit cost in mass production (**Figure 3**).

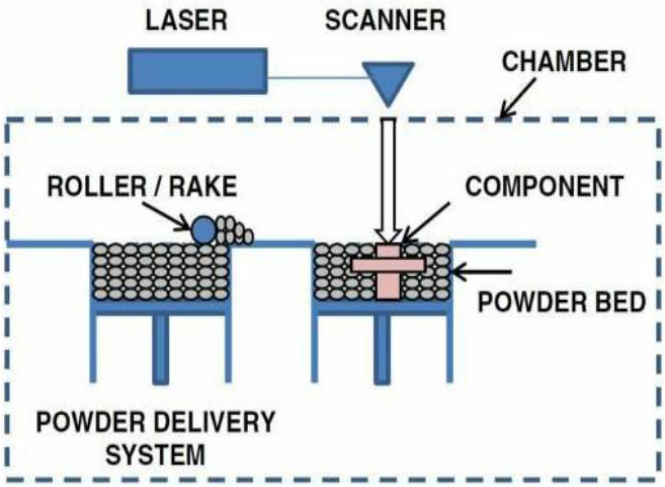


**Figure 3.** SLS procedure principle[5]
SLS: Selective laser sintering

## Selective Laser Melting (SLM) and Electron Beam Melting (EBM)

SLM is an AM method used to produce components with complex internal structures.[6]

These techniques fully melt metal powders (titanium, cobalt-chromium, stainless steel) using laser or electron beams.

- **Advantages:** High mechanical strength, excellent biocompatibility, porous structures for osseointegration.
- **Disadvantages:** High investment cost, long print time, need for post-heat treatment and support removal.
- **Clinical use:** Patient-specific sternal plates, cardiac stent prototypes, valve supports.
- **Cost:** Printers 250,000-1,000,000 USD; titanium powder 300-600 USD/kg.

## Binder Jetting and Material Jetting

In these systems, a binder agent is sprayed onto powder layers or photopolymer droplets are directly deposited layer by layer.

- **Advantages:** Fast production, multi-material and colored model printing.
- **Disadvantages:** Low mechanical strength, requires curing and infiltration.

- **Clinical use:** Colored models for demonstrating congenital heart diseases.
- **Cost:** Systems range from 50,000-200,000 USD.

## BIOMEDICAL PRINTING MATERIALS

Biomaterials used in implantable medical devices via 3D printing can be classified as biomedical polymers, metals, ceramics, composites, and derivatives. Between 2019-2025, the diversity of biocompatible materials increased rapidly.

- **Polymers:** PLA, PEEK, PETG, thermoplastic polyurethane (TPU)-for anatomical models and surgical guides.
- **Metals:** Ti6Al4V, cobalt-chromium-for permanent implants.
- **Composites:** Hydroxyapatite, graphene-reinforced polymers.
- **Biomaterials:** Hydrogel, collagen, alginate-for tissue scaffolds and bioprinting.
- **Polymers:** Biomedical polymer materials can be divided into two categories based on their properties: non-degradable and degradable. Non-degradable polymer materials include polyethylene, polypropylene, and polyformaldehyde. This type of material has good physical and mechanical properties and can also remain stable in a biological environment for long periods.

Collagen is an example of a degradable biological material.

PLA, PEEK, PETG, TPU-for anatomical models and surgical guides.

Biomedical metal materials refer to the metals or alloys used in biomaterials, also known as surgical implant metals. Clinically used biomedical metal materials mostly include stainless steel, titanium and titanium alloys, cobalt-chromium-molybdenum alloys, and medical precious metals.[7] They possess high fatigue strength, mechanical strength, and corrosion resistance. They are preferred in bone and joint prostheses, spinal implants, and cardiovascular implants.

### Biomedical Ceramic Materials

Biomedical ceramics are divided into three categories; biologically inert, active, and biodegradable. Bioinert ceramics include alumina, zirconium, and carbon. They have a stable structure, high strength, and good wear resistance. Among bioactive ceramics, materials such as bioglass,[8] which forms strong chemical bonds with tissues through chemical reactions in the body, can stimulate new bone growth. The main problems with biomedical ceramics are their low strength and toughness.

In cardiovascular surgery, PEEK and titanium are preferred for MRI compatibility and corrosion resistance.

- **Composites:** Hydroxyapatite, graphene-added polymers.

Biomedical composite materials consist of two or more different materials.[9] Composite materials significantly enhance the performance of a material by combining the superior properties of different materials. In addition to providing physical and chemical superiority, the composite material must also meet biocompatibility requirements. Biomedical composite materials are widely used to repair or replace human tissues and organs, enhance their function, and in the production of artificial organs.[10]

- **Biomaterials:** Hydrogel, collagen, alginate-for tissue scaffolding and bioprinting applications.

PEEK and titanium are particularly preferred in cardiovascular surgery due to their MRI compatibility and corrosion resistance.

## APPLICATIONS IN CARDIOVASCULAR AND THORACIC SURGERY

### Typical 3D Printed Implantable Medical Devices

3D printed implantable medical devices are applied to various parts of the human body. Typical products include vascular stents, heart valve prostheses, orthopedic implants, and artificial joint prostheses. Datasets can be obtained from MRI, CT, echocardiography, or rotational angiography.[11]

MRI datasets were used to print various right ventricular outflow tract models for preoperative guidance of percutaneous pulmonary valve implantation.[12]

### Sternum Closure and Rib Fracture Repair

Methods for repairing bone defects include autografts, allografts, and artificial bone substitute materials such as metal and polymer materials. Autologous bone transplantation requires two operations. However, due to their different structures, allografts can cause immune rejection and carry the risk of contracting infectious diseases from the donor. Therefore, research on artificial bone repair has become a focus of many scientists.

3D printing has three primary applications:

- **Preoperative planning:** Patient-specific heart models for surgical strategy.
- **Surgical simulation:** Pre-surgical practice, especially in congenital heart disease.
- **Patient-specific implants and instruments:** Cutting guides, suture templates, sternal plates.

## COST-EFFECTIVENESS ANALYSIS

- **Equipment and material costs:** FDM/SLA systems cost 3,000-10,000 USD; SLS/SLM 150,000-500,000 USD; materials range from 30 USD/kg (PLA) to 600 USD/kg (titanium).
- **Production efficiency:** 3D printing has reduced prototype/model fabrication time from weeks to hours. A heart model can cost <100 USD, while patient-specific metal implants remain cheaper than traditional machining.
- **Clinical contribution:** By reducing operation time and complications, 3D printing achieves indirect cost savings. Economic analyses (2022-2024) show 5-10% cost reduction in congenital surgeries.

## LIMITATIONS AND CHALLENGES

### Regulation: FDA and EU MDR require strict documentation.

- **Reproducibility:** Standardization of production and mechanical testing is limited.

- **Sterilization:** Some resins cannot withstand autoclave sterilization.
- **Hospital integration:** Image segmentation and model preparation are time-consuming.

## FUTURE PERSPECTIVES (2025 AND BEYOND)

Next-generation applications include bioprinting, multi-material hybrid printing, and 4D printing (materials changing shape over time). Future directions in cardiovascular surgery focus on biodegradable stents, patient-specific vascular grafts, and bioprinted myocardial patches.

Additionally, AI-assisted modeling and automated segmentation will further accelerate production.

## CONCLUSION

3D printing technologies have transformed cardiovascular surgery by enabling personalized and rapid production of surgical tools and implants. With the advancement of biocompatible materials such as titanium and PEEK, patient-specific implant fabrication is now clinically viable. Although challenges remain in cost and regulation, technological progress will likely make these systems standard surgical tools in the coming years.

## ETHICAL DECLARATIONS

### Peer Review Process

This review was externally peer-reviewed.

### Conflict of Interest

The author declares no conflicts of interest.

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### Author Contributions

The author is solely responsible for the entirety of conception, execution, analysis, and writing of the manuscript.

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