



REVIEW ARTICLE

3D PRINTING IN CUSTOMIZED DENTAL IMPLANTS: CURRENT CONCEPTS AND CLINICAL APPLICATIONS

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ABSTRACT

Three-dimensional (3D) printing, also known as additive manufacturing (AM) is one of the most promising innovations in implant dentistry, that allows the production of patient-specific implants with higher accuracy, better anatomical adaptability, and improved clinical results. This digital workflow minimizes material waste, production time, and surgical complexity while enabling precise personalization. A variety of additive manufacturing techniques including selective laser melting (SLM), electron beam melting (EBM), direct metal laser sintering (DMLS), stereolithography (SLA), digital light processing (DLP) and Fused Deposition Modeling (FDM) have significantly broadened the range of implant manufacturing. Titanium and titanium alloys continue to be the material of choice because of their superior mechanical properties, corrosion resistance and biocompatibility. Zirconia, polyether ether ketone (PEEK) and bioactive ceramics, however, are being increasingly investigated for specific therapeutic applications. This review summarizes the principles, digital processes, manufacturing technologies, biomaterials, clinical applications, benefits, drawbacks, and future prospects of 3D printing in personalized dental implants.

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INTRODUCTION

Dental implant therapy has become the gold standard for replacing missing teeth owing to its high long-term success rates, preservation of alveolar bone, and restoration of oral function and esthetics.^[1] Traditional implants are manufactured in standardized dimensions, so clinicians have to match the implant to the patient's bone. These implants have produced consistent results but may not be suitable for patients with complex anatomical variations, significant ridge resorption, congenital anomalies, traumatic injuries, or major maxillofacial malformations.^[2] In these cases, personalized implants providing specific solutions that fit the patient's anatomy properly are an attractive treatment option.^[3] Recent developments in digital imaging, computer-aided design (CAD), computer-aided manufacturing (CAM), and additive manufacturing have revolutionized implant dentistry.^[4] With the development of three-dimensional printing technology, clinicians are now able to design implants according to patient's bone availability, thus improving surgical accuracy

and prosthetic results. This technology enables the manufacturing of complex geometry implants that are not possible with conventional subtractive manufacturing methods.^[5] Furthermore, additive manufacturing can be used to introduce controlled porosity, lattice structures and internal channels which promote bone ingrowth and improve the biomechanical compatibility.^[6] The first step in designing patient-specific implants is to acquire anatomical data using CBCT or CT imaging. The implant is designed by using CAD software and the produced Digital Imaging and Communications in Medicine (DICOM) files are reconstructed into three-dimensional models by using specialized medical software.^[7] Then, the final stereolithography (STL) file is printed with a suitable additive manufacturing technology. Clinicians can utilize this computerized process to reduce intraoperative problems, optimize implant shape, model implant placement, and visualize anatomical structures prior to surgery. The process chain starts with imaging and segmentation, followed by CAD design, STL conversion, additive manufacturing, post-processing and surgical verification based on the uploaded evaluation.^[8] The advent of

additive manufacturing has expanded its role in digital dentistry from implant fabrication to the development of surgical guides, anatomical models, temporary restorations, orthodontic appliances, occlusal splints and maxillofacial prostheses. Rapid fabrication of custom devices has improved treatment planning, decreased laboratory procedures, reduced chairside time, and enhanced patient satisfaction.

Evolution of 3D Printing in Implant Dentistry: The birth of additive manufacturing came with the development of fast prototyping technology in the 1980s.^[9] Originally designed for the manufacturing of industrial products, the technology was modified for the medical industry because of its capacity to produce complex geometries directly from digital data. Since then, imaging technologies, design software, biomaterials and printing equipment have been developed, expanding its use in healthcare.^[10] The first applications in dentistry were limited to diagnostic models and surgery planning. The advent of high-resolution printers and improved biomaterials led to the rapid development of additive manufacturing for the production of implant surgical guides, frameworks for removable partial dentures, crowns, occlusal splints, clear aligners, and personalized dental implants.^[5] Literature review shows that additive manufacturing is extensively used for the production of custom-made root form dental implants, jaw fracture plates, aligners and other dental devices. One of the biggest turning points was the development of titanium root-form bespoke implants via electron beam melting.^[11] They have a natural emergence profile, mimic the structure of excised roots, and have improved primary stability.^[12] Selective laser melting was used to produce patient specific mandibular implants and complex maxillofacial reconstruction plates with better anatomical adaptability.^[13]

Less invasive procedures and prosthetically driven treatment planning are gaining importance in modern implant dentistry.^[14] Digital workflows enable physicians to easily communicate with intraoral scanning, CBCT imaging, virtual implant design, guided surgery and CAD/CAM prostheses.^[15] Such integration has greatly improved accuracy of implant placement, reduced surgical time and improved accuracy of prosthesis. Another major advancement is in the use of porous implant design. Traditional solid titanium implants are affected by stress shielding and marginal bone loss due to their much higher elastic modulus than that of cortical bone. The pore size, distribution and lattice structure are controlled, thus decreasing the stiffness of the implant and encouraging vascularization and bone ingrowth.^[16] The reviewed article shows that the use of porous titanium structures fabricated by additive manufacturing prolongs implant lifespan by decreasing stress shielding and improving osseointegration. Additive manufacturing has evolved from a simple rapid prototyping tool to a complete production platform for the production of finished implanted devices. In addition, future advances in artificial intelligence, topology optimization, biomimetic design, bioactive coatings, tissue engineering and four-dimensional printing are also expected to further revolutionize the future of personalized dental implant therapy.^[17]

Digital Workflow for Customized Dental Implants: A successful customized dental implant is built on a validated digital process which involves diagnostic imaging, virtual treatment planning, computer-aided design (CAD), additive manufacturing and prosthetic rehabilitation. Traditional

implant manufacture produces implants in standard sizes, while patient-specific implants are designed to the individual's anatomical morphology, providing better adaptability and biomechanical performance. The first step in the workflow is a complete evaluation of the patient, which includes a clinical examination and radiographic assessment. Cone-beam computed tomography (CBCT) has become the imaging modality of choice in implant dentistry due to its excellent spatial resolution, reduced radiation dose and ability to identify alveolar bone shape, essential anatomic structures and bone quality.^[18] Standard computed tomography (CT) or magnetic resonance imaging (MRI) provides more detailed anatomical information, when extensive maxillofacial reconstruction is required. The radiographic data are stored in the Digital Imaging and Communications in Medicine (DICOM) format and then imported into specialized medical imaging programs such as Mimics, 3D Slicer, InVesalius, or DeVIDE.^[7] Segmentation techniques allow for the construction of a three-dimensional anatomical model by isolating the region of interest.^[19] The stereolithography (STL) file exported from this digital model serves as the basis for the design of the implant. The uploaded review describes this workflow from imaging to segmentation, CAD design, STL conversion, additive manufacturing and post-processing. CAD tools enable clinicians and engineers to design implants that fit the patient's anatomy precisely. The dimensions of the implant, its thread geometry, emergence profile, abutment angulation, and lattice design can all be customized to the clinical situation.^[20] Finite element analysis (FEA) is increasingly being used during the design process to evaluate stress distribution under functional loads and to optimize implant geometry prior to manufacture.^[21] The STL file is digitally certified and sent to appropriate additive manufacturing equipment. After manufacture, implants undergo a number of post-processing steps including support removal, heat treatment, polishing, sandblasting, acid etching, ultrasonic cleaning and sterilization.^[22] These processes are crucial for obtaining the required surface qualities, dimensional accuracy, and mechanical properties for therapeutic use. The integration of intraoral scanners, facial scanners, virtual articulators and CAD/CAM restorative systems has further enhanced the digital process, allowing full digital rehabilitation from diagnosis to definitive prosthesis. Additive manufacturing is therefore an increasingly important part of modern digital implant dentistry.

Additive Manufacturing Technologies in Dental Implant Fabrication: Additive manufacturing technologies enable the production of personalized dental implants. The choice of technology depends on the material, the required accuracy, the surface quality, the mechanical properties and the intended therapeutic application.

Selective Laser Melting (SLM): One of the most popular methods for manufacturing metallic dental implants is selective laser melting.^[23] A high-energy laser is used to selectively melt thin layers of titanium or cobalt-chromium powder until the entire implant is built according to the CAD design. SLM's good dimensional accuracy allows the manufacturing of very complex porous lattice structures, which can't be manufactured by conventional machining.^[24] Controlled porosity reduces stress shielding by lowering the elastic modulus of titanium implants and increasing bone ingrowth. This method has been successfully used to manufacture customized root-form implants, mandibular

reconstruction plates, zygomatic implants, and craniofacial prostheses.

DMLS or direct metallic laser sintering: Direct Metal Laser Sintering uses a laser beam to sinter metallic particles layer by layer. DMLS and SLM are similar, but DMLS generally involves sintering or partial melting of powder particles. Owing to its better mechanical properties, high manufacturing accuracy and less material wastage, DMLS is widely used in the manufacturing of implant frameworks, customized abutments, removable partial denture frameworks and patient specific implants. This technique allows for the rapid fabrication of customized implants directly from digital files without the expensive milling procedures.^[25]

Electron beam melting, or EBM: Electron Beam Melting Titanium powder is melted with an electron beam instead of a laser, in a vacuum. Implants are designed with improved mechanical properties and reduced residual stresses in vacuum environment that prevents oxidation.^[26] Especially well suited for EBM fabrication are Ti-6Al-4V implants with very porous interior designs that promote quick osseointegration. The better anatomical adaptability and primary stability of EBM-customized root-form implants have shown good therapeutic results.^[27]

Stereolithography (SLA): Stereolithography is among the earliest additive manufacturing technologies used in dentistry. A focused ultraviolet laser selectively polymerizes liquid photopolymer resin to fabricate highly accurate three-dimensional objects.^[28] Although SLA is generally unsuitable for manufacturing definitive metallic implants, it is extensively used to produce Surgical guides, Dental models, Occlusal splints, Temporary restorations, Orthodontic appliances and Implant planning models. The technology offers superior surface smoothness and excellent dimensional accuracy, making it ideal for guided implant surgery.^[29]

Digital light processing (DLP): Like stereolithography, digital light processing uses a digital projector to cure an entire layer of resin at once. DLP has the advantages of faster fabrication, higher precision, smooth surface finish and shorter production time compared with SLA. DLP has gained popularity as a manufacturer of temporary prosthesis and surgical guides for implant placement.^[30]

Fused Deposition Modeling (FDM): This process uses a heated nozzle to extrude thermoplastic filaments and build objects. Typical materials are PLA, ABS, PEEK and polycarbonate. Despite its low cost and ease of use, FDM is not accurate enough to be used in the fabrication of definitive implants, but it is often used in education models, surgical planning, anatomical reproductions, and first prototypes of implants.^[9]

Biomaterials Used in Customized Dental Implants: The choice of material has a great influence on lifetime of the implant, biological response, mechanical properties and esthetic result.

Titanium and titanium alloys: Titanium is the gold standard for dental implants because of its excellent biocompatibility, low density, corrosion resistance, and mechanical strength. Commercially pure titanium and Ti-6Al-4V alloy are the most common materials used in additive manufacturing. Its

advantages include excellent osseointegration, high fatigue resistance, superior corrosion resistance, outstanding mechanical qualities, and long-term clinical success. Three-dimensional printing of titanium implants greatly improves the fabrication of porous structures that promote vascularization and bone ingrowth.^[31]

Zirconia: The esthetic appearance and good biological properties of zirconia has made it a popular alternative to titanium. Its main advantages include excellent esthetics, low plaque accumulation, high corrosion resistance, biocompatibility, and favorable soft tissue response.^[32] Recent advances in ceramic additive manufacturing now enable the fabrication of custom zirconia crowns and implants with improved dimensional accuracy. But zirconia is still more brittle than titanium and its clinical use is therefore restricted to high load situations.^[33]

Polyether Ether Ketone (PEEK): PEEK is an ultra performance thermoplastic polymer which is being researched more and more in the area of implant dentistry. Its elastic modulus is comparable to that of cortical bone and this enhances load transfer and decreases stress shielding. Its benefits are radiolucency, light weight, excellent fatigue resistance, high chemical resistance, and good biomechanical compatibility.^[34] In general, surface modifications and bioactive coatings are necessary to elevate the relatively poor osseointegration of pristine PEEK implants.^[35]

Cobalt-Chromium Alloys: The cobalt-chromium alloys possess very good mechanical strength and wear resistance. They are often used in metal-ceramic restorations, implant-supported prosthetic frameworks and removable partial dentures. Direct metal laser sintering makes it much easier and less labor-intensive to fabricate custom cobalt-chromium frameworks.^[36]

Bioactive ceramics: The mineral makeup of natural bone closely resembles hydroxyapatite, tricalcium phosphate, bioactive glass and calcium phosphate ceramics. These compounds promote rapid osseointegration, bone regeneration and osteoconduction. Thus, bioactive ceramics are commonly used as implant coatings or bone graft substitutes, rather than permanent load bearing implants.^[37]

Metals free: Recent work has involved biodegradable magnesium, zinc and iron alloys that gradually degrade as new bone tissue develops. Potential applications are pharmaceutical delivery systems, scaffolds for bone regeneration, and temporary implants. Although they have potential, these materials are still difficult to control degradation rates and need more research before they can be used routinely in the clinic.^[38]

Surface modification and osseointegration: The long-term success of implants depends not only on the implant geometry but also on the biological interaction of the implant surfaces with the surrounding bone.^[39] Modern additive manufacturing can produce implants with tailored surface roughness, interconnected porosity, and biomimetic microstructures that accelerate bone healing. Surface treatments such as sandblasting, acid etching, anodization, laser texturing, hydroxyapatite coating, calcium phosphate deposition and bioactive peptide functionalization further promote osteoblast attachment and differentiation.

Controlled porosity structures promote bone ingrowth, nutrition transport and vascular invasion, while decreasing stress shielding. Together, these properties improve long-term survival of the implant, accelerate osseointegration and improve primary stability.^[40]

Clinical Applications of 3D Printing in Customized Dental Implants; Implant dentistry has used additive manufacturing for much more than just the fabrication of traditional dental implants. Treatment results, surgical precision and diagnostic accuracy have all improved through anatomical models, maxillofacial prosthesis, patient-specific surgical guides and customized implants. Doctors can now marry digital imaging with computer-aided design and manufacturing to give patients personalized care based on their own anatomy.

Customized Root-Analogue Implants: One of the most promising applications of 3D printing in implant dentistry is in root-analogue implants (RAIs). Unlike conventional cylindrical implants, RAIs are based on CBCT imaging and CAD software to accurately reproduce the morphology of the extracted tooth root. The customized implant can be directly inserted into the extraction socket after an atraumatic extraction, avoiding surgical trauma and preserving the natural alveolar architecture. The close adaptation between implant and socket results in improved primary stability and less extensive osteotomy preparation. Recent advances in electron beam melting (EBM) and selective laser melting (SLM) technologies have allowed for the fabrication of titanium root-analogue implants with interconnected porous surfaces, which promote rapid osseointegration and early bone regeneration. These implants have shown beneficial clinical effects though long-term randomized clinical trials are still needed before normal clinical use.^[41]

Patient-Specific Dental Implants: Patient-Specific Dental Implants Patients with traumatic defects, congenital malformations, severe resorption of the alveolar ridge and failed implant therapy often do not have enough bone volume for traditional implant placement. Patient-specific custom implants can be designed directly from CBCT data, providing an exact fit to the available bone anatomy.^[42] This individualized technique eliminates many of the disadvantages of standard implant proportions and greatly reduces the need for complex bone augmentation procedures. The submitted review discusses the potential for additive manufacturing to create personalized implants with complex internal porosity architecture and complex external geometry, which would be difficult to produce using traditional fabrication methods. These designs promote bone regeneration and improve implant stability.^[43]

Maxillofacial Reconstruction: Maxillofacial Repair Revolution in 3D printing has changed the maxillofacial reconstruction after the removal of tumor, trauma, congenital defects and osteonecrosis. The development of virtual planning software has allowed to produce mandibular implants and titanium reconstructive plates tailored for each patient prior to surgery. This technique has many benefits including accurate anatomical reconstruction, less intra-operative plate bending, less operating time, better facial symmetry, better functional rehabilitation and better esthetic result. In cases of mandibular continuity deficits, where traditional reconstruction plates sometimes require extensive intraoperative adaptation, the use of customized reconstruction

implants has become valuable.^[44] Guided Implant Surgery One of the most popular applications of 3D printing is to design surgical guides.

Guided Implant Surgery: Static surgical guides are manufactured through stereolithography (SLA) or digital light processing (DLP) after virtual implant planning. These guides precisely transfer the digital treatment plan into the patient's mouth controlling the position, depth and angulation of drilling of the implant.^[45] The clinical benefits of guided surgery are numerous, including better prosthetically driven implant positioning, less surgical trauma, increased accuracy of implant placement, reduced surgical time, less postoperative discomfort, and greater predictability. The accuracy of implant dentistry has been significantly improved by combining guided surgery with customized implants.^[29]

Bone Tissue Engineering: Tissue Engineering for Bone Additive manufacturing has also contributed significantly to regenerative implant dentistry by fabricating personalized scaffolds for bone regeneration. Three-dimensional printed scaffolds can be made of titanium, hydroxyapatite, collagen, tricalcium phosphate, polycaprolactone (PCL) or composite biomaterials. Their complex and interconnected porosity structure promotes angiogenesis, cell migration, nutrient transport, osteoblast proliferation and new bone formation. According to the uploaded review, metallic biomaterials, ceramics, synthetic polymers (e.g., PCL, PLA, and PLGA), and natural polymers (e.g., collagen and chitosan) are all being investigated for tissue engineering applications as they can be customized to offer suitable mechanical properties and degradation profiles.^[46]

Advantages of 3D Printing in Customized Dental Implants

Additive manufacturing has many important advantages over traditional ways of producing things. The specific anatomy of the patient is considered during the manufacturing of the implants which enhances fit, primary stability and esthetic results.



Figure 1. Digital workflow for customized dental implant fabrication, illustrating the integration of clinical diagnosis, digital planning, CAD, material selection, additive/ subtractive manufacturing, and final implant placement

While subtractive manufacturing cannot create complex interior architectures, porous surfaces, or lattice structures, layer-by-layer fabrication can. Interconnected porosity and controlled pore size facilitate biological fixation, bone ingrowth and vascularization. Additive manufacturing is more environmentally friendly compared to traditional milling because it uses the materials necessary for fabrication.

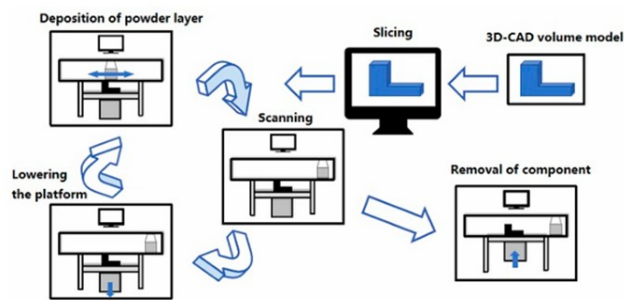


Figure 2. The processing flow of SLM

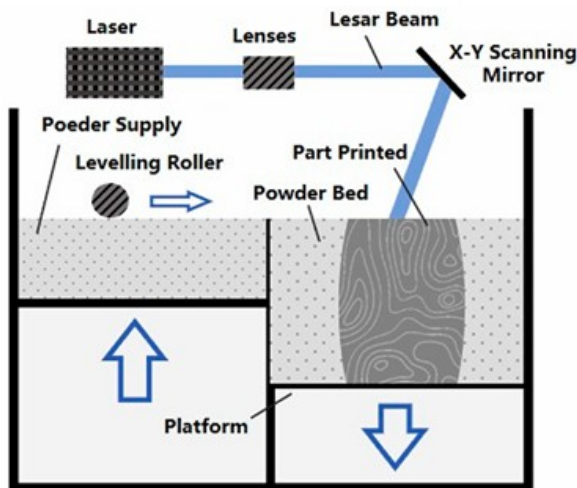


Figure 3. The processing flow of EBM

Digital workflows reduce laboratory procedures and enable fast production of patient-specific implants and surgical guides. Customized surgical guides together with digital planning improve the precision of implant positioning and reduce surgical complications. Printed anatomical representations aid patients' understanding and informed consent. Additive manufacturing can easily be integrated into digital prosthodontics, CBCT, intraoral scanners and CAD/CAM systems.

Limitations and Challenges: It has many benefits but there are several disadvantages to additive manufacturing, which have affect its broad acceptance in healthcare settings. Industrial-grade printers, complex software and post-processing equipment still require a large initial investment. Multidisciplinary collaboration between prosthodontists, oral surgeons, biomedical engineers and design experts is needed to produce bespoke implants. While the dimensional accuracy has greatly improved, the precision of the final implant may still be affected by elements including imaging quality, segmentation faults, STL conversion, printer calibration and post-processing. The posted review suggests that the accuracy of the implant is dependent on the image acquisition, three-dimensional reconstruction, and STL processing and printing settings that should be carefully optimized. Regulatory approval is also an issue, as patient-specific implants require stringent validation of manufacturing processes, sterilization protocols and extended clinical performance. Furthermore, there are still few long-term randomized controlled clinical trials that assess personalized implants versus traditional implant systems.

Future Perspectives: In the future, personalized implant dentistry will not only be about producing implants, but also about developing complex regenerative implant systems.

AI: Artificial intelligence (AI) is increasingly being applied in digital implant planning for automated segmentation, implant selection, surgical simulation, and prosthetic design. AI-assisted workflows could improve treatment predictability, reduce operator variability and increase efficiency.

4D (Four-dimensional) printing: Four-dimensional printing is the next stage of additive manufacturing. Unlike static 3D-printed objects, 4D-printed architectures are composed of smart materials that can change their shape or function in response to external stimuli like temperature, pH, moisture or mechanical force. Potential applications include self-adjusting implants, shape-memory scaffolds, smart orthodontic devices, and adaptive tissue engineering constructs. The review posted states that dynamic scaffolds and 4D bioprinting are promising future directions for regenerative medicine and customized tissue engineering.

Drug-Eluting and Bioactive Implants: New implant designs incorporate growth factors, stem cells, antimicrobial peptides, antibacterial coatings and controlled drug delivery mechanisms to promote healing and lower peri-implant infection.

Printer for bioprinting: Bioprinting produces biologically functional tissues by combining living cells, biomaterials and growth factors. Future applications may include bioengineered periodontal ligament, alveolar bone regeneration, gingival tissue engineering, and whole tooth regeneration, although these are still in experimental stages. These developments could signal a shift in implant dentistry from prosthetic replacement to biological regeneration.

SUMMARY

Three-dimensional printing has revolutionized customized dental implant therapy by allowing the fabrication of patient-specific implants with unprecedented precision, geometric complexity, and biological performance. A full digital workflow, integrating CBCT imaging, CAD/CAM technology and additive manufacturing, has been developed to enhance diagnosis, treatment planning, surgical accuracy and prosthetic rehabilitation. Titanium-based additive manufacturing techniques, such as electron beam melting, direct metal laser sintering, and selective laser melting, allow for the production of porous implants that enhance osseointegration and decrease stress shielding. Meanwhile, developments in zirconia, PEEK, bioactive ceramics, biodegradable metals and tissue-engineering scaffolds are increasing the range of biomaterials for implant dentistry. Customized root-analogue implants, patient-specific implants, guided implant surgery, maxillofacial reconstruction, and regenerative bone scaffolds are all in clinical use. Additive manufacturing is set to become an important part of precision dentistry, although some challenges in terms of cost, regulatory approval and the need for long-term clinical evidence remain. Upcoming developments in artificial intelligence, topology optimization, bioactive surface modification, 4D printing and bioprinting are anticipated to further enhance implant function and ease the transition to individualized regenerative dental healthcare. The

safe and predictable incorporation of personalized 3D-printed dental implants into routine clinical practice will require ongoing interdisciplinary research and carefully planned clinical studies to establish established methods.

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Glossary of Abbreviations

Abbreviation	Definition
3D	Three-dimensional
4D	Four-dimensional
AI	Artificial intelligence
AM	Additive manufacturing
CAD	Computer-aided design
CAM	Computer-aided manufacturing
CBCT	Cone-beam computed tomography
CT	Computed tomography
DICOM	Digital Imaging and Communications in Medicine
DLP	Digital light processing
DMLS	Direct metal laser sintering
EBM	Electron beam melting
FDM	Fused deposition modelling
FEA	Finite element analysis
PCL	Polycaprolactone
PEEK	Polyether ether ketone
RAI	Root-analogue implants
SLM	Selective laser melting
STL	Stereolithography

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