3D printing- An Futuristic art and science in dentistry

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Abstract:

By gradually adding material layer by layer, 3D printing, sometimes referred to as additive manufacturing, is the method of creating a solid three-dimensional object from a computer-aided design (CAD) model. The development of personalized medical devices and implants, as well as the creation of models for pre-operative planning, medical education, training, simulation, and research, are all made possible by the widespread use of 3D printing in research and clinical settings, particularly in the healthcare industry. Building high-quality, precise, and functional patient-specific models using 3D printing is related to and dependent upon medical imaging techniques because these imaging techniques are in charge of gathering the necessary data. An overview of 3D printing in dentistry is included in this article.

Keywords: Printing, Three-Dimensional,Dentistry, Craniofacial Abnormalities, Stereolithography, Computer-Aided Design, Manufacturing, Computer-Assisted

Introduction:

A rapidly evolving technology, three-dimensional (3D) printing has found widespread acceptance and use in dentistry (Kessler, Hickel and Reymus, 2020). According to Jain, Supriya, and Gupta (2016), it is sometimes referred to as additive manufacturing (AM), rapid prototyping, or layered manufacturing[1]. According to Dawood et al. (2015), the phrase "3D printing" is typically used to refer to a manufacturing process that develops an object by adding layers one at a time.[2] The primary concept behind this breakthrough is that the 3D model is divided into numerous thin layers, and the manufacturing or assembling equipment uses geometric data to construct each layer successively until the desired end product is finished. Making a virtual model that is close enough to the desired model is the first step in everything (Cummins 2010).[3] The anatomy that needs to be provided to the 3D model can be examined and recorded using scanners. The 3D model is cut, and then it is ready to be loaded into the proper kind of 3D printer.[4] This may be accomplished using USB, Wi-Fi, or SD cards. The model or item is prepared for 3D printing in layers once the record is transferred to the printer. Each 2D image is used by the 3D printer to create a three-dimensional object. It is possible to create objects with geometry ranging from simple to sophisticated.[5] This process is referred to as slicing (Liu, Leu and Schmitt, 2006). Rapid prototyping and additive manufacturing are two terms that are more frequently and accurately used to describe it (Andonovi).[6]

The diagnosis and planning of oral disease treatments both benefit greatly from 3D imaging. Giving digital images a physical form that can be felt and handled would give practitioners additional options for operative skills, patient communication, and treatment planning. It may also serve as a teaching tool for dentistry students to develop their practical abilities (Moser, Santander and Quast, 2018).[7] As 3D printers become more widely used, 3D modelling and printing technology advance (Huang and Lin, 2017). With the development of 3D modelling and imaging technologies like intraoral scanning, CBCT, and CAD/CAM, 3D printing has drawn considerable interest and gained prominence in the field of dentistry (Gabor et al., 2017; Sawhney and Jose, 2018).[8]

History of 3d printing (table 1)[9,10]:

Year	Inventions
1981	The first ever 3D model was built by Hideo Kodama in Nagoya Municipal Industrial Research Institute by using photopolymers
1984	Charles Hull invented stereolithography, i.e. process of building 3D models using digital data. This new technology was instantly popular with inventors, who could now build and test their prototypes without paying a hefty manufacturing fee.
1992	The world's first Stereolithographic Apparatus (SLA) machine was built, which made it possible to build complex parts, layer by layer; along with the world's first Selective Laser Sintering (SLS) machine, which could shoot laser at a powder instead of photopolymer liquid
1999	The world's first 3D printed organ was transplanted in humans, when scientists at Wake Forest Institute for Regenerative medicine 3D printed synthetic scaffolds of a human bladder and coated them with human cells.
2006	The first SLS machine became commercially viable and then Object built a 3D printer that could print in multiple materials. Then Shapeways and Makerbot were formed, which provided designers with DIY kits for manufacturing along with feedback from consumers.
2008	Darwin a self-replicating 3D printer was built.
2009	scientists have built a functional miniature kidney, then a prosthetic leg and then bioprinted the first blood vessels
2016	Modern additive manufacturing technology was introduced approximately three decades ago (Stansbury and Idacavage, 2016) and its application in dentistry is recent.

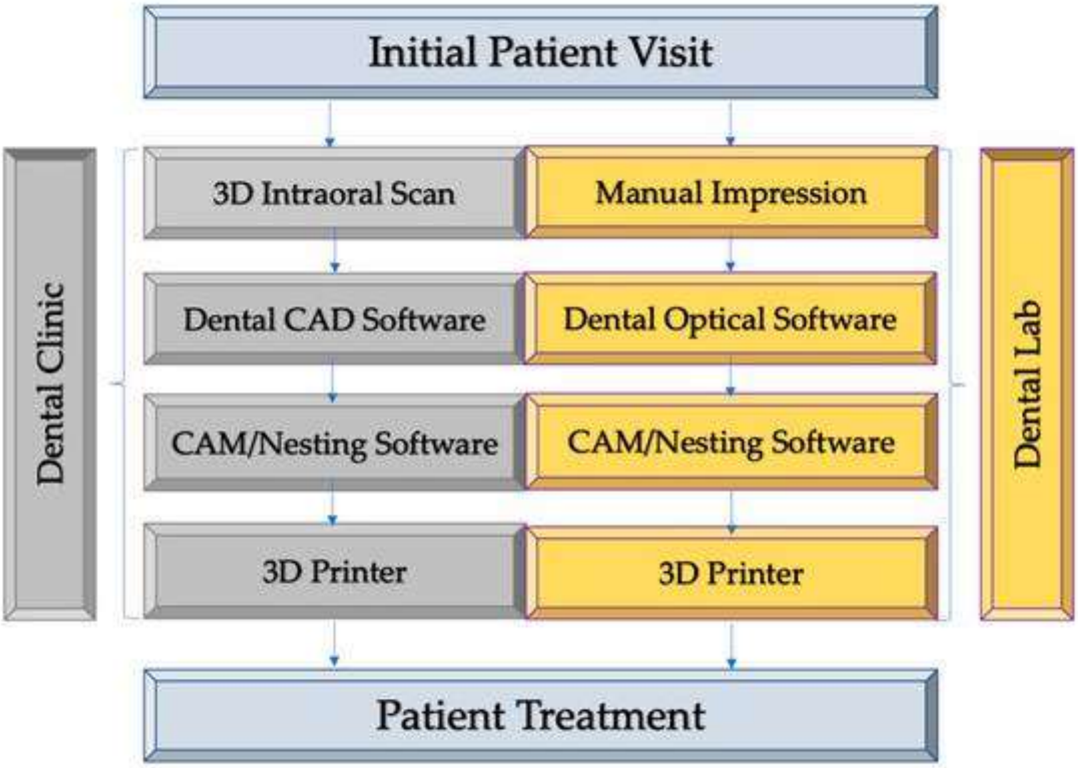
Workflow of 3D printing:

The term "digital dentistry" refers to a broad range of digital technologies, including the use of accurate intraoral scanners, 3D imaging tools, CAD/CAM software, and 3D printers, which can improve and increase efficiency in comparison to more conventional analogue techniques like taking impressions, 2D imaging, and traditional subtractive manufacturing methods.[11]

These tools can be used with conventional techniques and incorporated into numerous procedural workflow phases. In order to improve patient treatment outcomes, virtual planning is increasingly employed in conjunction with 3D printing at the pre-treatment/pre-surgical stage. Using 3D intraoral scanners, the patient's anatomy is precisely captured to serve as the basis for the virtual planning process.Although the performance of various intraoral scanners may differ, it has been demonstrated that clinically acceptable accuracy is consistently attainable. As an alternative, dental labs will be able to scan conventional imprints and plaster models using desktop optical scanners.[12]

CAD software can then be used to plan treatments and create digital 3D models using the patient data collected by scanners. Using today's dentistry software, virtual settings, like designing smiles, can make use of highly graphic interfaces and well-known design procedures. Following the creation of the treatment, 3D models may be easily exported for manufacture using CAM software and then delivered to a 3D printer. 3D printers may be used in both healthcare settings and labs to produce a variety of objects thanks to their ability to function in tandem with the accuracy of digital 3D models to create a variety of products for treatment, such as dentures, surgical guides and splints, aligners, retainers, and mock-ups (figure 1).[13]

Process of 3d printing in dentistry



Techniques of 3d printing:

The following techniques are employed for Additive manufacturing or 3D printing of various applications in dentistry.[14]

1. Stereolithography (SLA).

2. Fused Deposition Modeling (FDM).

3. Selective Laser Sintering

4. Photopolymer Jetting

5. Electron Beam Melting (EBM)

6. Power binder printers

7. Direct light processing

Materials used in 3D printers[14-16]:

Materials	Uses
Plastic:	• It is the most commonly used material as it has a high appeal due to its firmness, flexibility, smoothness and a wide range of colors. • Plastic products are made in FDM printers. • Plastics used for 3D printing are made using one of the following- Polyastic Acid (PLA), Acrylonitrile butadiene styrene (ABS), Polyvinyl alcohol plastic (PVA) or polycarbonate (PC).

	PLA is the most eco-friendly option as it is made from sugar cane and corn starch and hence, is biodegradable.
Powder:	Most common powders used are Polyamide (Nylon) and Alumide
Resins:	These are of three types- high detail resins, paintable resins and transparent resins
Metal:	It is the second most popular material. Metals generally used are- Stainless-Steel, Bronze, Gold, Nickel, Aluminium and Titanium.
Carbon fiber:	It is mostly used in combination with plastics.
Graphite and graphene:	Graphene has high strength and conductivity, so is preferred for making solar panels, touch screens etc
Nitinol:	Due to its super elasticity, it is used to make medical implants
Paper:	Paper printed designs are far more realistic than flat illustrations and so are preferred for demonstrations.

Types of the additive 3D printing process in dentistry (table 3)[17]:

Types	Clinical features
Stereolithography	• The oldest and most frequently used technique of 3D printing technique in dentistry is SLA. The principle of SLA is that it is constructed on a layered structure of an entity made of a UV-sensitive liquid monomer which is polymerized and solidified by a laser.
Digital Light Processing	• Digital light processing (DLP) is the second method that is generally used. • DLP contains a microsystem consisting of a rectangular mirror arrangement called a "digital micromirror device". The angle of the micromirrors can be individually adjusted which acts as light switches and projects the light from the source as individual pixels onto the projection surface. The advantage of DLP technology over the SLA technique is that every single layer can be cured with a single shot of laser exposure by producing patterned laser light rather than scanning separately one after the other with the laser. • A high cost of manufacturing is the disadvantage of DLP
Photopolymer Jetting and Material Jetting	In the photopolymer jetting and material jetting processes, the object is built up in layers by a print head with several linear nozzles. The principle can be compared to that of a conventional inkjet printer. Instead of ink, a liquid photo monomer is used for photopolymer jetting, and for material jetting wax is used. Afterward, the monomer is cured in layers by UV light or the wax hardens thermally on the building platform. • This technique is relatively fast but the high cost of manufacturing is a disadvantage.
Binder Jetting:	It is a type of photopolymer jetting where an adhesive is applied to a powdery substrate using pressure nozzles. • Additional support structures are not necessary, as the printed entity is completely bounded by a supportive substrate. If metal and glass powders are used, the object can be exposed to a sintering process in which the adhesive is burned out.

	• Due to high adhesive content, the resulting items exhibit high sinter shrinkage and porosity and should be infiltrated subsequently. • Due to the complicated geometries in dentistry, the binder jetting process using powder/adhesive is restricted mostly to surgical planning models
Selective Laser Sintering/Laser Melting:	In the laser melting process all powdery materials that can be sintered or melted by laser radiation and solidified after cooling can generally be used. • The material used can range from plastics and metallic materials to ceramic materials. In dentistry, these methods are used mainly for metals. • The terms ''laser sintering'' and ''laser melting'' are understood conflictingly. • The two processes are further divided into numerous subgroups, some of which represent the brand names of certain companies (eg; laser CUSING). • However, the basic printer building principle is alike. Low cost is the advantage and high maintenance is the disadvantage of laser melting
Fused Filament Fabrication:	• The melt layer process was developed over 20 years ago by the founder of Stratasys (Edina, MN, USA) and protected by the trade name ''fused deposition modeling.'' The process is called fused deposition modeling. The non-patented term is ''fused filament fabrication (FFF)'' which works according to the principle of strand extrusion. • Thermoplastic materials, like polylactides, acrylonitrile butadiene styrene, and waxes, are provided as semifinished products in various strand thicknesses to the extruder, where they are melted in the hot end and applied to the building board with the aid of a die at the respective x-y coordinate. • Heated construction chambers are used to diminish heat distortion in cases of uneven cooling. • After completion of one plane, the next plane (z-axis) is started. Low cost is the advantage and low accuracy is the disadvantage of this method.
Bioprinting:	• Bioprinting employs the use of biomaterials, cells, or cell factors as a "bio-ink" to fabricate tissue structures. Parameters like biocompatibility, cell viability, and 13 cellular microenvironments of the biomaterial can greatly alter the printed product. The goal of this method is to design 3D artificial tissues that consist of a scaffold, cells, and an environment that is similar to the real environment of the human body. • 3D bioprinting attains these three essential constituents as it is an extremely effective and precise method to create artificial tissue in-vitro. • Materials used are alginate, fibrin, collagen, PLGA (poly lactic-co-glycolic acid), tricalcium phosphate, chitosan, and hyaluronan. It creates structure with living cells, soft and hard tissue scaffolds, 3- dimensional hydrogels, ceramics, and hydrogels
Subtractive Manufacturing in Dentistry (CAD-CAM)	• Dentistry has an extensive association with subtractive manufacturing more usually defined as 'milling'. • CADCAM is the elimination of material to shape an object. CAD-CAM for the construction of crown copings is now a synonym with current dental technology. • This technology allows the use of materials that would be difficult to work with, and reduces labor-intensive artisanal production procedures, permitting the dental lab technician to improve his hand skills on more innovative features of the manufacturing process

Benefits of additive 3d printing over subtractive printing:

The ability to plan 3D printed objects on computers, allowing for an infinite number of silhouettes with varied degrees of complexity, is a key advantage of

additive technology. The ability to still modify the mechanical and visual features during 3D printing is a feature that has received some attention. Using CAD-CAM, where the production business modifies the prefabricated blocks' physical characteristics, this is not conceivable. Additive manufacturing is a cornerstone of digital dentistry because it offers the option for customization, quick, easy availability at a cheaper cost. Also, compared to subtractive procedures like milling, the additive manufacturing process wastes extremely little material.[18,19]

Modern dentistry is aware of materials made to function with CAD-CAM and serve as a replacement for the more conventional precious metal casting alloys, whose prices have recently increased exponentially. This use of technology makes it easier to work with materials that would otherwise be challenging and eliminates labor-intensive skilled processes, which frees up the dental technician to concentrate on more imaginative parts of production. Each time a dentist performs a restoration process, it is specific to that patient. Every restoration will also have inherent complexity that calls for highly accurate reproduction of complex geometry. Although multi-axis CAD-CAM milling systems may tolerate this up to a certain limit, the procedure is as inefficient as the object and is as slow.[20]

Applications of 3D printing in dentistry:

1. Oral medicine and radiology:

Three-dimensional-virtual environment presents an important role in preoperative planning and surgery simulation. The virtual reality (VR) has the ability to rightfully contemplate the soft tissue and bony changes. It provides surgeons with the best possible scenario for preoperative treatment planning. It made it easy to plan and execute surgeries virtually with immediate loading of the prostheses. These simulations allow surgeons to prepare the required instruments for execution of the procedure. A simulated model of the planned outcome can be 3D printed, serving the patient to visualize the treatment outcome and also assisting in receiving the patient’s consent before performing the surgery. 3D printed models are also being used in research to study the origin and treatment of cancer.[21]

2. Oral maxillofacial surgery[22-28]:

3D printing helps in facial reconstruction surgeries. The implant for the surgery is shaped on 3D surgical model before the surgery, reducing trauma to the tissue and the operating time.

Similarly, in cranio-maxillofacial surgeries, 3D printed models are used for pre-bending of reconstruction titanium plates on a 3D model prior to skull resections, help us restore the correct position of remaining bones accurately and reducing the surgery time.

3D models are also used for preoperative distraction osteogenesis drive selection.

3D models are extremely accurate prototype models that help new surgeons ease into preoperative planning and improving postoperative esthetics and facial contour symmetry, for example, the reconstruction of maxilla, mandible and orbits. This helps to inspect anatomy preoperatively, practice different treatment modalities, and reduce surgery time and minimize errors.

3D models serve as surgical guides for surgical resections or osteotomies based on preoperative imaging to provide higher Patient Safety Indicators, which is even more important in metal implant surgeries.

Surgical guides in cranio-maxillofacial surgery are also used for bone resections and free flap construction using a fibula free flap.

3D printed surgical guides are also used for accurate treatment planning for rib grafting and fixation in mandibular ramus deficiencies.

3D models are also used in orthognathic surgeries. Orthognathic surgery is a type of corrective surgery done to restore proper anatomy and functional relationship in patients with dentofacial skeletal anamolies. 3D models help achieve preplanned operations for performing accurate osteotomies and perfect positioning of unaligned jaw. Printing of cutting guides for osteotomies and 3D printed patient specific fixating plates for accurate positioning of jaws, greatly reduce mistakes made due to human error.

3D printed intraoperative dental splints are used for accurate repositioning of jaw/midface with 3D preoperative planning in case of facial fractures.

3D printed models make for high-accuracy prostheses that enhance the aesthetic and psychological states of a patient suffering from poor aesthetics due to scarring, deformation or asymmetry.

3D printing is also used to make patient-specific implants (PSI), based on 3D imaging to provide perfectly fitting implants to restore proper anatomy, symmetry, relation and function. After mandibular resections and avulsion injuries, titanium implants, for load-bearing reconstruction, combined with autogenous bone grafts and PSI integrated with dental implants are used for dental arch and occlusion restoration.

Polyether ether ketone (PEEK) implants are used to restore zygomatico-orbital complex and mandibular angle deficiencies for trauma injuries, orbital wall defects and in syndromic patients.

PSI are used in orthopedics for printing customized external fixators to treat fractures, and in cervical spine reconstruction.

PSI are used in neurosurgery in cranioplasty for reconstructing skull defects. Similarly, in thoracic surgery, PSI are used to reconstruct chest wall and in ophthalmology for ocular prosthesis.

3. Prosthetic dentistry[29,30]

Custom trays can be manufactured or 3D printed from computerised scans of impressions or models. Model printing directly from intraoral scan helps quick fabrication of prosthesis.

In RPD, resin framework can be tried in a patient's mouth before casting. In fixed and removable prosthodontics, restorations could be designed using CAD software and crowns, bridges, copings, abutments, etc can be printed using 3D printers.

Printing of coping or full contour resin patterns can avoid the process of making manual wax patterns, followed by which, the consequences of wax distortion can also be minimized. The marginal fit is of paramount importance for long term success of restorations.

Provisional crown and bridge resins were 3D printed and showed higher accuracy and good mechanical properties and marginal fit when compared to conventional ones.

4. Implant dentistry[31-33]

The use of tooth implants has rapidly evolved and widely accepted for replacing single or multiple missing teeth in the last two decades.

The use of 3D printing technology has gained popularity and acceptance in dental implantology due to the introduction of guidelines for a surgical procedure which implies the usage of surgical guides for insertion of dental implants.

Jugaad technique involves the use of available dental materials such as PMMA, impression compounds, etc as index material in the fabrication of surgical guides. Costs of this planning are minimal; it produces the desired functional outcome as well. 3D printing helps in the easy production of complex geometry dental implants and surgery guides or drill guides.

3D printers also print bone tissue favouring the requirements of the patient that can act as a biomimetic scaffold in the mouth for bone cell enhancement, tissue growth and differentiation.

3D printed bone implants can replace the deficient part using biocompatible materials like PEEK (polyetheretherketone). The integrity of the implant is important in minimising the stress transfer to the bone.

3D printing is capable of producing implants with bone-like morphology, in order to reduce the stress-induced on the bone.

Prefabricated dental implant surgical guides can be used for verifying or guiding the proper location, angulation and rotational positioning of the implant prior to the placement in order to provide better aesthetics and functionally stable prosthesis.

5. Endodontic dentistry[34]

3D printing serves as a solution for endodontic challenges; some of which include guided access with pulp canal application in autotransplantation, accurately locating the osteotomy perforation sites, pre-surgical planning, educational models and stent guides.

6. Orthodontic dentistry[35]

Indirect bracket-bonding splints, occlusal splints, aligners, etc can be 3D printed. Adjustment or customization in terms of angulation, bending, etc is possible during the manufacture of brackets. In addition to this, it is now virtually possible to present the changes that will be caused by the braces in advance.

7. Periodontics[36]

Another area of expertise in dentistry where 3D printing is employed is periodontics, where the prime focus is regenerative periodontal research. Few of the major periodontal post-operative complications include mobility, loss of attachment, furcation, painful and bleeding gums, gingivitis, cellulitis and MRSA mediated skin and soft tissue infections. It is recommended to keep the gingival margins relieved and retracted to avoid such complications. 3D printed guides are used for aesthetic gingival correction.

Advantages of 3D dentistry:

When 3D printed restorations are compared with conventionally made ones, their high-quality precision, accuracy, detail recording capacity and finely finished restorations make 3D printing technology the winner among all other available processing methods in dentistry. Its higher efficiency, resolution, flexibility, ease and quick fabrication, lesser material wastage due to additive procedures, superior diagnostic and learning abilities stand for the importance of 3D printing in dentistry.[37,38]

Disadvantages of 3D dentistry:

3D printing is a very expensive endeavor. With the development of virtual treatment planning technology, usage of 3D printed models for treatment planning has lessened. There is no legislation or regulation regarding 3D printing to stop criminals from buying 3D printers and printing guns, weapons etc to commit crimes. There are no parental controls to stop children from misusing it. 3D printed objects can sometimes be of a lower quality than if they were traditionally manufactured, like lower functionality and resistance. Mass printing of objects instead of manufacturing via traditional methods can lead to an economic imbalance. As 3D printing is a computer-controlled technique, it reduced human labour and work force requirement, which lead to unemployment. This will also affect import of construction materials used in traditional methods as different materials are used for 3D printing.[39,40]

Futuristic directions in 3D printing:

4D printing is an upcoming technology that has immense possibilities. Skylar Tibbitt’s and his coworkers designed self-folding structures that reshape under certain environmental conditions. They converted the steady 3D printing materials into actively changing objects by this approach. Thus, 4D printing helps in the making of materials that shape-shift over a certain time or space. 4D-printed materials can move in different directions as programmed before they are constructed. Regulating the track of the motion of 4D-printed materials in restorative dentistry can eradicate the use of dental etching and bonding systems as they rely more on retention via mechanical means and not chemical aids.[41]

Future applications can include:

4D-printed restorative materials in dentistry that can alter their shape as well as position from the center to the margins in a known time and can prevent fracture or marginal leakage. Designing orthodontic appliances with a controlled, self-folding motion to move the teeth in the required direction and angulation is possible. This amazing technology if made use of, can progress similarly to CAD-CAM and 3D printing and thus change the scope of dentistry[41]

Conclusion:

Over the past few decades, 3D printing has empowered clinicians, as well as improved diagnostic and surgical skills as it permitted for realistic training, better conception, and surgical planning. In dentistry, this expertise has brought in a revolution as it provided maximum accuracy in a small clinical setup and short chair side time. More explorations are required especially in India so that we can provide a holistic approach to ameliorate the health and wellbeing of our patients.

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Nil

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Nil

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