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Review Article

Applications of additive manufacturing in dentistry: A review

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Abstract: Additive manufacturing (AM) or 3D printing has been hailed as the third industrial revolution as it has caused a paradigm shift in the way objects have been manufactured. Conventionally, converting a raw material to a fully finished and assembled, usable product comprises several steps which can be eliminated by using this process as functional products can be created directly from the raw material at a fraction of the time originally consumed. Thus, AM has found applications in several sectors including automotive, aerospace, printed electronics, and healthcare. AM is increasingly being used in the healthcare sector, given its potential to fabricate patient-specific customized implants with required accuracy and precision. Implantable heart valves, rib cages, and bones are some of the examples where AM technologies are used. A vast variety of materials including ceramics, metals, polymers, and composites have been processed to fabricate intricate implants using 3D printing. The applications of AM in dentistry include maxillofacial implants, dentures, and other prosthetic aids. It may also be used in surgical training and planning, as anatomical models can be created at ease using AM. This article gives an overview of the AM process and reviews in detail the applications of 3D printing in dentistry. © 2017 Wiley Periodicals, Inc. J Biomed Mater Res Part B: Appl Biomater 00B: 000–000, 2017.

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INTRODUCTION

Since the advent of additive manufacturing (AM) or 3D printing as it is commonly known, customization has become a feasible reality. It is possible to create customized implants at a fraction of the time and cost originally entailed owing to the versatility of the 3D printing process.[1]

While the automobile,[1] art, and aerospace sectors have benefitted considerably,[1,2] the major sector that commands a large share in the 3D printing industry is the medical devices sector.[2–4] This is primarily because each person has a different anatomy as compared to others and the use of a mass produced implant leads to a significant compromise in the recovery time and anatomical accuracy. Hence there is a need to manufacture custom made devices and implants.[3,4] In the medical device industry, 3D printing is commonly used in creating orthopedic implants.[5–7] It is also used in creating artificial tissues and organs. Heart valves, knee meniscus are some of the organs that have been successfully replicated through 3D Printing.[6,7] A 3D-printed rib cage has been designed for patients suffering from loss of ribs due to accidents and other conditions.[8]

Dentistry is one avenue in medicine that had greatly benefitted from 3D printing. Creating artificial teeth and dental implants has become all the more easily owing to the ability of the process to create them rapidly, sometimes within a dentist's office itself.[9,10]

The oral cavity or mouth comprises the upper jaw (maxilla), lower jaw (mandible), 32 teeth (16 attached to each jaw), muscles, nerves, and blood vessels.[11,12] These tissues are prone to infection or accidental damage. Three-dimensional printing plays a vital role in creating life-like implants to replace these damaged tissues.

PROCESS OF 3D PRINTING

The process of 3D printing entails the creation of an object from the raw material layer by layer. A virtual image of the object is sliced into several layers, which are fused together by means of a binding agent or through sintering.[9,10] As observed in Figure 1, the process of 3D printing any implant comprises a series of procedures that begin with obtaining the image of the organ. Based on the image of the organ, the implant is designed and is then built up layer by layer.[13,14] The process of creating any model organ or implant begins with a scan to obtain an image of the organ. Several two-dimensional images are obtained as seen in

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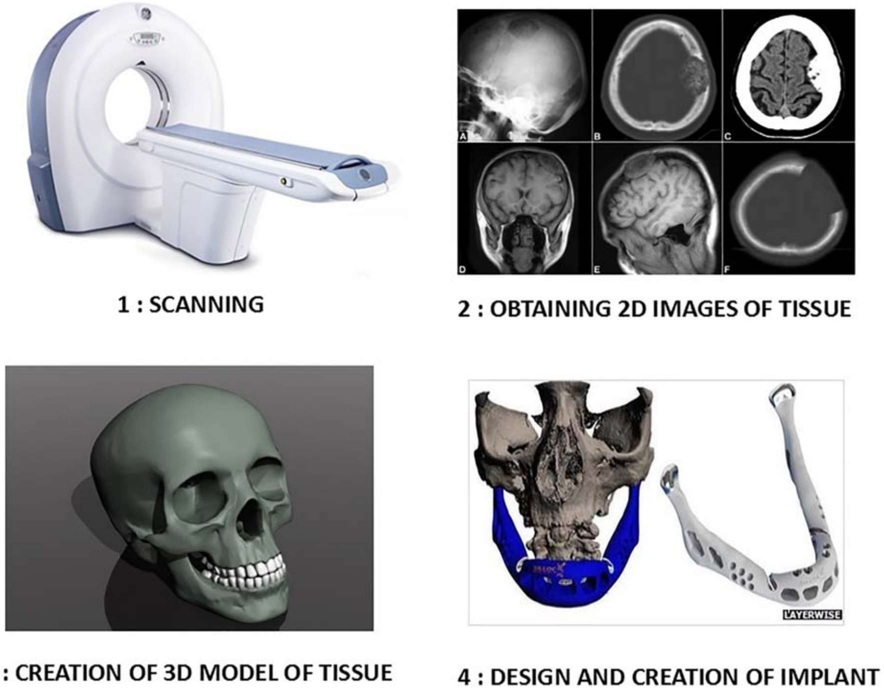

FIGURE 1. Process applied in medical 3D printing.[13]

Figure 2.[13] This is then placed together to obtain a model that is then verified and then then printed using a 3D Printer.

Imaging

Several methods of imaging are available to obtain the 3D model of the organ. While magnetic resonance imaging (MRI) is the preferred mode of scanning for soft tissues,[14,15] computed tomography (CT) is used for hard tissues.[15] The image is obtained in cross-sectional layers.[13–15] As the quality of the image plays an important role in the final product, an optimum thickness of each layer obtained should be a minimum of 1 mm. On the other hand, thicker layers will result in a stepped structure. However, such fallacies in

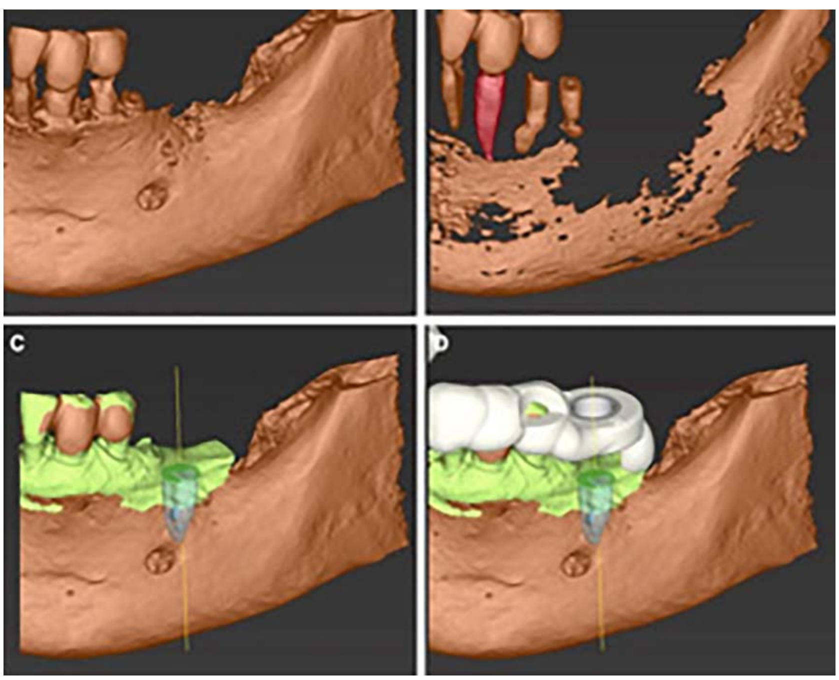

FIGURE 2. Designing and positioning of implant using postprocessing software[20]: (A, B) Image of patients anatomy; (C, D) Planning of positioning of implant.

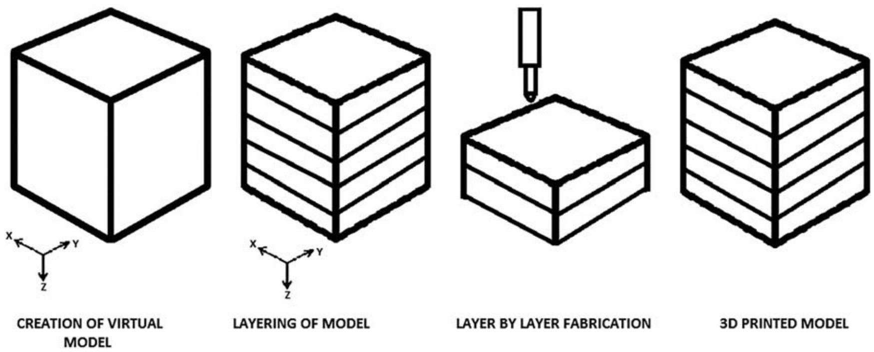

FIGURE 3. Process of rapid prototyping.[21]

imaging can be partially overcome using algorithms that remove the steps and smoothen them to form curves.[16,17]

Additionally, images of the organ may also be obtained by using photoprogrammetry applications such as 123D Catch, where a 3D image of the organ may be generated by obtaining images of the object in several orientations and placing these together to form a virtual object. While using photoprogrammetry applications is convenient, it only allows for surface reconstruction as the object is not scanned across the cross-section.[18]

The postprocessing of the image is done using image processing software such as MIMICS.[19] Here, the model obtained from the scan is smoothened. The features of the implant are designed to suit the anatomical requirements of the person.

Three-dimensional printing

The images obtained are stacked together to form a structure.[21] This process of slicing a structure into two-dimensional images and rebuilding it to from a structure is known as tessellation. In 3D printing, the model is built layer by layer as illustrated in Figure 3. The dimensional accuracy of the object along its vertical axis depends on the thickness of each layer, which may vary from one millimetre to a few microns, depending on the printer, the material, and the complexity of the object.[22–24]

The material may be fabricated to form a hollow, semi-solid, or solid structure. This may be done by varying the infill ratio (the ratio of filled area to unfilled area in a layer) as seen in Figure 4.

While some materials can be fabricated by melting a wire layer over layer, other machines that make use of metals and ceramics use lasers or other binding agents to fuse one layer to the previous layer. The process of 3D Printing may be either direct or indirect. Direct 3D printing involves the printing of the object by the 3D printer. Whereas in indirect 3D printing, a mold is prepared using 3D Printing and the object to be made is cast in the mold.[25,26] Direct 3D printing is preferred in cases where accuracy may be compromised on. In indirect 3D printing, the mold may be further processed to ensure the accuracy of the implant.

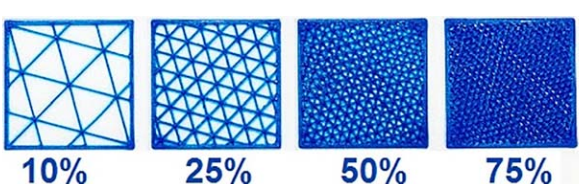

FIGURE 4. Creating hollow and solid structures in 3D printing.

MATERIALS

Three types of materials, that is, metals, ceramics, and polymers are primarily used in 3D printing. While metals and ceramics are used in applications which require the implant to be inert, polymers are used in applications where the material is required to degrade to facilitate the growth of a tissue. Composite implants comprising a mixture of materials are used in applications, where a single material alone may not serve the required functionality.

The range of materials that can be processed using 3D printing is extensive. From metals to cells, several thousands of materials can be fabricated using one of the many AM processes. A combination of processes may also be used to create a single part. The list of materials and the processes used to fabricate them are enlisted as follows.

APPLICATIONS

The applications of 3D printing in dentistry are many. Some of the applications include creating implants for deformed jaw bones, dentures, and false teeth. Three-dimensional printing may also be used in cases where a variety of materials is required as it is a very versatile manufacturing process. Some of the applications of 3D printing in dentistry are explained in Table I.

Maxillofacial implants

In some cases, patients suffer fracture of the chin and jaw owing to trauma. In other patients, cancer may spread to a region of the jaw and the infected tissue needs to be removed. Three-dimensional printing may be applied to replace the entire jaw or a portion of the jaw.[50,51] As observed in Figure (5 and 3)D printed metallic implants to replace the jaw may be created. This is done through a powder metallurgy based AM process known as selective laser melting (SLM). In this process, the powdered form of the metal is melted and fused to the previous layer, thereby creating a three-dimensional object. The implant created is

TABLE I. Applications of 3D Printing in Dentistry

S. No.	Type of Material	Material	Advantages	Fabrication Process	References
1	Metal	Titanium	Bioinert, corrosion resistant	Selective laser sintering, direct metal laser sintering, selective laser melting, direct metal deposition	27,28
		Stainless steel	Bioinert, corrosion resistance		29
		Aluminum	High volume-to mass ratio		30
		Cobalt chrome	Corrosion resistant		31
2	Ceramics	Alumina	Bioinert, same color as tooth, corrosion resistant	Selective laser sintering, stereolithography, inkjet 3D printing, thermoplastic printing	2,32
		Zirconia	Bioinert, same color as tooth, corrosion resistant		33
3	Polymers	Poly lactide	Bioresorbable, odontogenic	Stereolithography, fuse deposition modelling, electro hydrodynamic jetting	34,35
		Poly caprolactone	Bioresorbable		36
		Poly glycolide	Bioresorbable		37
		Acrylic	Bioresorbable		38

a bioinert one that remains inert and does not undergo any changes when reacted upon by bodily fluids. The implant was created using powdered titanium.

Bioresorbable maxillary and mandibular implants using calcium phosphates have also been fabricated.[39,40,52] The implant is made either by dissolving the material in a photo curable mix and allowing the implant to set in the presence of a suitable light[39] or by mixing the material with a suitable binder and allowing the implant to dry.[40] In this process, the layers of calcium are bound to each other by means of a strong binder or glue that holds the layers together. Calcium phosphates are commonly found in the body. As a result, the implant is bioresorbable in nature and eliminates the need for an immunosuppressant. Similar studies have been conducted using tricalcium phosphate and hydroxyl apatite[53] for bone reconstruction and favorable results such as integration of the implant into the native tissue have been observed.

Dentures and crowns

A replacement for teeth and the tissues that are connected to it is known as a denture. A denture is usually removable and can be cleaned on a daily basis.[54,55] In the case of aged patients or accident victims who have lost all their teeth, complete dentures are required. Partial dentures are required for patients who have lost one or few teeth.

TABLE II. Dental Material Selection

S. No.	Application	Materials	Process	Properties	References
1	Maxillo-facial implants	Titanium	Selective laser sintering, direct metal deposition	Bioinert	27,28
		Calcium phosphate	Photopolymerization, inkjet 3D printing	Bioactive or bioresorbable, mechanical compliance similar to tooth	39,40
2	Dentures and crowns	Cobalt chrome	Selective laser sintering	Corrosion resistant	31,41
		Plastic	Fuse deposition modeling, ink-jet 3D printing	Ease of fabrication	42
		Alumina	Thermoplastic printing	Bioinert	2,32
		Zirconia	Direct inkjet printing, thermoplastic printing	Bioinert	33
3	Anatomical and training models	Metals	Selective laser sintering, direct metal laser sintering, selective laser melting, direct metal deposition	Sturdy models	45
		Veroglaze	Polyjet 3D printing	Same color as tooth	44
		Nylon	Stereo-lithography, selective laser sintering		45
		Plaster	Indirect 3D Printing, Inkjet Printing	Easy of fabrication, inexpensive	46
4	Scaffolds for tissue engineering	Poly lactide	Fused deposition modelling, electrospinning, stereo-lithography	Ease of fabrication, bioresorbable, stereo-lithography	34–38
		Poly Caprolactone	E-jetting, electrospinning	Ease of Fabrication	36
		Ceramics	Selective laser sintering, polyjet printing	Same color as teeth, good mechanical properties	2,32,33
5	Scaffold-less tissue engineering	Cells	Microextrusion	Eliminates need for immunosuppressant	47–49

FIGURE 5. 3D printed titanium implant.

AM has also been used in creating partial and complete dentures. Metallic dentures have been created using a process known as direct metal laser sintering (DMLS). An alloy comprising cobalt, chromium, and molybdenum was used to create the dentures.[54–58] Plastics have also been used in creating false teeth and temporary dentures.[34–38] Fused deposition modelling (FDM) is used to melt plastic wires and deposit them in the shape of the denture. Also, a mold may be created by means of 3D printing and the plastic may be injected into the mold.[42] This method may be used to create solid parts and hollow and semi-hollow structures. To create semi-hollow structures, the layers are built in a lattice wise pattern as compared to filled layers.

The Food and Drug Administration (FDA) authority of the United States has granted approval for a material that may be used to form a denture base. The material, a light curable polymer, can be fabricated into a base by stereolithography.[59] Studies are being conducted to create antimicrobial dentures by 3D printing.[60]

Dental crowns are structures that are used to cover a damaged tooth.[61] They offer protection to the tooth against further damage and improve the appearance of the tooth. Crowns are made either using inert metals such as gold and silver or ceramics. The color of the ceramic crowns matches with that of the other teeth and gives the crown a natural appearance. These crowns may be manufactured through selective laser sintering or selective laser melting depending on the type of crown.

Anatomical and training models

The first application of AM in medicine was the creation of anatomically accurate models that could be used to train surgeons and healthcare personnel. Models of the jaw, teeth, and other organs have been created to enable the surgeon to plan for the surgery prior to the surgery being conducted. Preparing for the surgery enabled for more accuracy and lesser error in the surgery. Superior materials are being engineering to facilitate creation of better models.[44–46]

The process of creating a model begins with obtaining the three-dimensional model of the organ, which may be obtained either through CT or MRI and then creating the 3D model. In cases of a damaged organ, the anatomical model may be used to assess the extent of damage and evaluate the treatment options. In the case where an implant is necessary, the anatomical model may be used to evaluate the fit of the implant on the original tissue, prior to surgery, thereby cutting down on surgery time.[13–15]

Tissue engineering

Tissue engineering is the process through which native tissue is generated by using a combination of cells and materials. The cells may be deposited on a 3D structure known as a scaffold (scaffold-based tissue engineering) or may be allowed to proliferate without a scaffold (scaffold-less tissue engineering).[62–66]

In scaffold-less tissue engineering, polymeric materials are required to construct support structures for the movement of blood and nutrients. Direct printing of cells to form functional tissues, thereby eliminating the need of a scaffold is also being researched upon. Cells in the form of spheroids may be deposited layer by layer.[47] This application may be used in dental tissue regeneration, where the pulp cavity may be filled with cells in a preset pattern and microstructured biomaterials. Here, the necessity for a scaffold is eliminated as the scaffolds have been arranged in a pattern and do not require a scaffold to facilitate the arrangement and stabilization of cells. Hydrogels may be used as carriers to enable the deposition of cells.[48] In this process, bioinks comprising cells, media, and other stabilizing agents are used in lieu of plastics and other materials used in printing.[49] While 3D printed tissue engineering is still in its nascent stages of development, the applications are many and cannot be ignored.

CHALLENGES

The characteristics of AM, namely, the ability to allow for customizations, versatility in materials, and ease of manufacturing and quick production time, make the process an attractive one. Another advantage of the process is less material wastage, as unlike machining and other subtractive manufacturing processes, very little or no material is discarded. However, despite the numerous advantages that the process offers, there are a few drawbacks to the process that need to be addressed.

Three-dimensional printers are easy to obtain and have resulted in an upward trend in the do-it-yourself culture. This may pose a hazard when people try to create a product that they are unsure of and bypass testing protocols. Cases have been reported where people have printed their own orthodontic braces. While this may work for some, there is a high chance of failure and this may be detrimental to the patient.

Another drawback of AM is the reliance of the process on the initial image. Patients with metallic implants may not be able to undergo MRI, thus causing difficulty in creating implants for such patients.

Three-dimensional printing has come a long way and is here to stay. The versatility of the materials that are processed by AM play a key role in ensuring the sustenance of the process. A range of materials beginning with ceramics to the softer materials can be printed. Thus, soft- and hard-tissue models can be created. However, this process also has its own disadvantages. Not all materials can be processed by AM; certain materials may not be completely compatible. As a result, it becomes difficult to fabricate them. Replacement materials may or may not be as suited or as competent as their predecessor materials.

Also, cost is a major factor as specialized machinery costs a lot. While AM by itself consumes less time, prefabrication and postprocessing may be intensive.

FUTURE OUTLOOK

Every day, new materials are being discovered and new methods to process them are being identified. Multimaterial printing, where a combination of several materials may be used to create a single part, is now becoming a reality. This is done by incorporating the elements required for two or more different materials in a single system. For example in porcelain-fused-to-metal dental crowns, for a given layer, the metallic portion may be fabricated first, followed by the fabrication of the ceramic section. This may be repeated in layers to get a multimaterial object. In some cases where specific mechanical properties are required, a combination of materials may be used to tune the properties.

Tissue engineering is now becoming a reality and 3D printing contributes to this field as biomaterials which serve as scaffolds to guide the growth of the tissue may be created through AM. Scaffolds for several tissues including tendons, ligaments, and so forth have been fabricated and tested in the *in vitro* setting. While these scaffolds may be used for tissue regeneration, scaffolds for drug testing are also being developed.

Studies have been carried out on implants manufactured through AM and it is inferred that these implants are as efficient as conventionally fabricated implants. Three-dimensional printed implants have been found to be viable solutions that aid in periodontal healing. It is also observed that the 3D Printing of teeth helps in creating accurate models that resemble native tooth, which can be used to replace the tooth in case of tooth loss.

Owing to the recent advancements in technology, it is believed that AM will play a greater role in healthcare in general and dentistry in particular in the near future.

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