

Current status and applications of additive manufacturing in dentistry: A literature-based review

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ARTICLE INFO

Keywords:

Additive manufacturing (AM)
3D scanning
Dentistry
Applications
Implants

ABSTRACT

Objective: To study the current status and applications of additive manufacturing (AM) in dentistry along with various technologies, benefits and future scope.

Methods: A significant number of relevant research papers on the additive manufacturing application in dentistry are identified through Scopus and studied using bibliometric analysis that shows an increasing trend of research in this field. This paper briefly describes various types of AM technologies with their accuracy, pros and cons along with different dental materials. Paper also discusses various benefits of AM in dentistry and steps used to create 3D printed dental model using this technology. Further, ten major AM applications in dentistry are identified along with primary references and objectives.

Results: Additive manufacturing is an innovative technique moving towards the customised production of dental implants and other dental tools using computer-aided design (CAD) data. This technology is used to manufacture elaborate dental crowns, bridges, orthodontic braces and can also various other models, devices and instruments with lesser time and cost. With the help of this disruptive innovation, dental implants are fabricated accurately as per patient data captured by the dental 3D scanner. The application of this technology is also being explored for the precise manufacturing of removal prosthetics, aligners, surgical templates for implants and produce models that for the planning of treatment and preoperative positioning of the jaws.

1. Introduction

Additive manufacturing is used to create a 3D solid object directly from the digital 3D CAD data under computer control. Various areas of manufacturing such as industries, defence, aerospace, art, medical and design are adopting by additive manufacturing for customisation and rapid production. Nowadays, it has various applications in the field of dentistry in which manufacturing of personalised dentistry models is possible. The technology successfully produces drill guides for dental implants.^{1,2}

AM process starts with a virtual image which is created by a 3D scanner or CAD software and generates product by different AM technologies. AM technologies fulfil the complex challenges in medical as well as in dentistry. These technologies are now available to improve patient outcomes. The two leading technologies prominent in the area of dentistry are stereolithography (SLA) generally used for aligner fabrication, and another is direct metal laser sintering (DMLS) which is

capable of producing high-quality metal dental crown and appliance frames.^{3–5}

Implant surgeries are performed mostly by hand. During this procedure, dentists first scan the patient's jaw and drill the patient's mouth by taking help of scanned image. This technique works on imagination so it is not so accurate.^{6,7} Additive manufacturing is a sophisticated method for pinpointing the best location to drill. It improves the accuracy of surgery by correctly creating an entire set of denture that comfortably fit in the patient's mouth. AM technology is now becoming accessible. It provides better health care and offers needful information for diagnosis and treatment to the dentist. It also has different applications in medical areas during performing of complex surgery which is helpful to improve patient outcome.^{8–10}

2. Types of additive manufacturing technologies

The fundamental principle of AM is to directly create a 3D physical

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<https://doi.org/10.1016/j.jobcr.2019.04.004>

Received 3 July 2018; Received in revised form 13 October 2018; Accepted 15 April 2019

Available online 16 April 2019

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model by adding layer by layer technique from CAD model (generated with the help of designing software or by the 3D scanner, CT, MRI). There are various AM technologies used to build product layer by layer; each adopts different methods of production of the physical model as discussed below:

- **Stereolithography (SLA):** Products are built with the application of ultraviolet laser inside a vat of resin. Limited availability of materials useable with this technology as it uses light-sensitive polymers. It gives better surface finish and has lesser wastage of raw material.^{11,12}
- **Selective laser sintering (SLS):** In this additive manufacturing technology, it accomplishes sintering with the application of a laser beam. The material used is in the form of powder, and laser sinters the powder.^{13,14}
- **Fused deposition modelling (FDM):** Product is manufactured as similar to the extrusion process, where a heated thermoplastic material is added layer by layer to fabricate a model. In this process, the print head consists of multi-nozzle and extrudes different types of material at the same time.^{15,16}
- **Direct metal laser sintering (DMLS):** This technology is used to produce metal parts with high accuracy and better mechanical strength. In this technology, the metal material is added layer by layer and a laser beam is used to fuse powder at a definite point.^{17,18}
- **Polyjet 3D printing (PJP):** Undertaking the manufacture of part through UV-curable acrylic plastic. It uses various types of printing materials. In medical and dentistry field, model printed by this technology provides a better understanding of patient anatomy.^{19,20}
- **Inkjet 3D printing (IJP):** This technology use different fluids such as polymer solution provided in the form of liquid and deposited layer by layer to build a product. It prints varieties of materials with less time and cost.^{21,22}
- **Laminated Object Manufacturing (LOM):** 3D models are fabricated by adding layers of the defined sheet of materials. A laser is used to cut sheet material as per the required cross-section. Adhesives are used to combine the layers and generated by repeating the steps.^{23,24}
- **Colour-Jet-Printing (CJP):** This technology uses powder as a core material, and binder as a resin and the part is built through spreading of core material in the layer, over the build platform using a roller. Printing head jets/spray binder (adhesive) on the powder layer at specified points as decided by the CAD software, thus a colourful product is built (printed) which has extensive usage in the medical field.^{25,26}
- **Electron Beam Melting (EBM):** Powerful electron beam is used to build product layer by layer using a metal powder by command of the CAD model with exact geometry. Under a vacuum, the raw material is stored and fused by an electron beam.^{27,28}
- **Multi-Jet-Printing (MJP):** In this technology, nozzles are used to spray binding of liquid onto metallic or ceramic powder to create a thin solid layer. After production of the model, it must be sintered in the furnace to increase the strength.^{29,30}

All these additive manufacturing technologies offer different dental materials having different accuracy. Table 1 describes the different dental material, accuracy along with the pros and cons of each AM technology.

3D physical model printed by AM provides an accurate perception of a patient's anatomy to the dentist and the surgeon. Implants of a specific patient are created with geometric freedom and solve day to day challenges in dentistry.

3. Research questions

This article addresses the following research questions:

RQ1: To study different technologies of additive manufacturing, their accuracy, pros and cons with different dental materials.

RQ2: To identify relevant research papers on the additive manufacturing application in dentistry through Scopus and studied using bibliometric analysis.

RQ3: To study various benefits and steps used to create a 3D printed dental model using this technology.

RQ4: To identify significance applications of additive manufacturing in dentistry along with primary references and objectives.

4. Benefits of additive manufacturing in dentistry

In dentistry, there are various requirements for the patients; such as crown, implants and bridges. Various AM technologies are beneficial for dentistry. Binding jet technology is used to manufacture dental prostheses. Various parameters are taken such as drying powder level, binder amount, drying time and powder spreading speed. The result shows that it provides an accurate implant with low cost and better strength.³¹ Additive manufacturing is used to manufacture patient specific eruption guidance appliances, thereby increasing patient comfort and reducing overall cost of the model.³² Binding Jet 3D printing technology is used to produce partial denture by using metallic powder. Micro-computed tomography is used to scan the existing framework for obtaining a 3D printed model. The result shows that it helps to achieve more than 99% density with controlled shrinkage at a lesser cost. It is highly compatible to produce complex shape dental implant with exact dimensions.³³ The comparison of the accuracy of dental restoration manufactured through additive manufacturing and subtractive manufacturing method using wax or zirconia milling is undertaken. The result shows that the accuracy of dental restorations manufactured by additive manufacturing technique is higher than that of subtractive methods. AM is also a digital method which stores inventory in digital form; as a result, it also reduced inventory cost.³⁴ The experimental analysis for dimensional accuracy is done for teeth manufactured by FDM technique. The intraoral 3D scanner is used to create a 3D digital model and manufactured model by three different layer thicknesses. Dimensional accuracy of the model is evaluated by GOM Inspect software, which shows that the reducing layer thickness easily achieves a high level of accuracy.³⁵ Additive manufacturing fulfils the customised requirements of dentistry in lesser time and cost.^{2,6,8,10} Following are the significant benefits obtained through the adoption of AM in dentistry:

- Faster and accurate service
- Cost-effective
- Determine depth and width of teeth
- Easily fabricate customised implants
- Reduce fabrication time
- With its digital storage, there is considerable inventory reduction of physical models
- Rapidly produce custom design
- Accurate sizing for implants

By using AM, the dentist can now use a variety of materials for prosthodontics such as ceramics and metal alloys. It produces dental model optimally with high accuracy.

5. Research status on additive manufacturing applications in dentistry

Identified research article related to this area through Scopus database till September 2018 by searching keywords as “Additive Manufacturing” Dentistry” and found 70 research articles published in this field. Here we observed from the data, that first paper got published in 2009, and now the number of publications has risen. Fig. 1 shows year-wise publications from 2009 to September 2018.

Table 1
Additive manufacturing technologies with accuracy and its pros and cons with different dental materials.

S No	AM technology	Approximate Accuracy	Dental Material	Pros	Cons
1	Stereolithography	50–55 µm	- Acrylate photopolymer - Plastic - Ceramic	- It has high speed that producing functional parts within a day - Used for making anatomical model, prosthetics, master patterns for injection moulding and various metal casting	- Part obtain are more fragile - Not used for mass production - Machine cost is high
2	Selective laser sintering	45–50 µm	- Thermoplastics - Powder - Plastic - Metals	- No supporting material required - Parts possess high strength and stiffness - Various finishing possibilities - Good chemical resistance	- Printed parts have a porous surface - Sealed by applying a coating such as a cyanoacrylate
3	Fused deposition modelling	35–40 µm	- Ceramic - Polycarbonate - Acrylonitrile butadiene styrene (ABS) - polypropylene - Polyesters	- Print prototype functional and end-user parts - Produced high strength part - It is cost-effective and waterproof - Multiple material colours are available - Use for printing of Polyether ether ketone (PEEK) materials	- Often leads to ribbing that shows lines from each layer. - Polishing or sanding can be added to remove these lines. - Supports material may be required - Temperature fluctuations during production could lead to delamination.
4	Direct metal laser sintering	20–35 µm	- Titanium - Cobalt - Aluminium - Bronze alloy - Steel - Stainless steel - Nickel alloy	- Manufactures high strength parts - Good accuracy of final Product - Manufactures efficiently any complicated shape product	- Manufactured parts can be porous which have a rough surface depending on the material used - Cause shrinking and warping of manufactured parts
5	Polyjet 3D printing	20–85 µm	Photopolymers	- Produced complex shapes, intricate details and delicate features - More flexible process successfully used in healthcare and dentistry sector - Used to produce replica of the organ - Manufacture accurate crowns, bridges and orthodontic appliances - Print any complex design part - It quickly produced parts - Applied in health care such as print organ - Ability to produce larger-scaled models - It is fast and accurate - Environmentally friendly - Good strength - Not health threatening - Produce high-quality colour print - Very quickly and quietly - Being portable, it becomes useful for small business or the home office environment.	- Compaction and quality of the materials are inferior to that of injected moulds. - Not suitable for mass production
6	Inkjet 3D printing	35–40 µm	- Powder - Liquid binder		- Size of objects is limited - Machine cost is high
7	Laminated Object Manufacturing	60–70 µm	- Metal - Plastic		- Need for describing, which requires much labour - Stability of paper objects is not as excellent as materials used by other AM technology
8	Colour-Jet-Printing	23–30 µm	- Gypsum powder - Binder		- Colour print cost of the product is high. - Low mechanical strength
9	Electron Beam Melting	40–50 µm	- Metal powder - Titanium	- Ability to achieve a high energy level in a narrow beam - Vacuum environment eliminates impurities - Lower power consumption as well as lower maintenance - Produce smooth and precise parts with highly complex - High production speed - No extra finishing treatments required	- Requires vacuum which is costly and needs maintaining - Electron beam technology produces X-rays while in operation - No ceramic materials available commercially yet - Lack of precise information on ceramics AM specifications - High-performance polymer currently prioritised.
10	Multi-Jet Printing	25–35 µm	- Powder - Plastics		

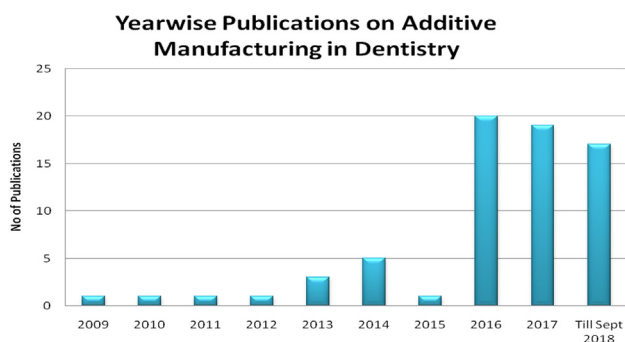


Fig. 1. Additive manufacturing applications in dentistry: Year-wise publications (Source: Scopus).

Journal of Prosthetic Dentistry have highest publications of nine in this field by the application of AM. Dental Materials journal have two publications is at position 2. Biomed Research International, Rapid Prototyping Journal, Journal of Dental Research and various other journals have one each. By the application of AM in the field of dentistry, engineering area has maximum utilisation of 27%. However, dentistry contributes 23%, Materials Science 16%, Biochemistry, Genetics and Molecular Biology 11%, Medicine 5%, Computer science 3% and other areas also contribute 14%.

From Scopus data, it has analysed that applications of additive manufacturing are increasing in the area of dentistry. Thus these technologies/machines are becoming commercially viable and acceptable in the field of dentistry.

6. Steps used to create a 3D printed dental model using additive manufacturing

3D physical models build by the additive manufacturing technologies provide complete and better information to the surgeon. Table 2 discusses the various steps used to create 3D printed dental models.

Dental 3D scanners are now available for designing implants (denture, prosthetics, or aligners). It consists of a light source and camera/s. Projector project light on the surface of the patient part and camera capture the data in the point cloud. It captures multiple images of the patient part and further merged these images to form a complete 3D digital model. This 3D digital model easily modifies design through the use of different software and easily printed by AM technologies.

Table 2

Steps to create a 3D printed dental model by using additive manufacturing.

S. No	Step used	Description	References
1	Digital 3D model of the patient's mouth	Digital models are created by 3D scanners in the form of cloud data with fast and accurate dimensions	Haleem and Javaid 2018 ³⁶ ; Kumar et al., 2018 ³⁷
2	Modification in design	- Used 3D scanner for precise scanning of patient mouth and teeth - After scanning, it is essential to ensure that the dental model will fit perfectly by adjusting shape, size and position - Easy modification in design is done through the use of different software and the associated AM technology	Azari and Nikzad 2009 ³⁸ ; Tahmaseb et al., 2014 ³⁹
3	3D printing	- Fabricate 3D solid object directly from the 3D digital file by the addition of materials layer by layer - Dental implants are manufactured using different AM technologies according to the specification of printing material - Post-processing is used to increase the physical property and strength of the implant - Reliable for reconstruction of precise teeth and other tools used in dentistry - It is cost effective as compared to the other manufacturing techniques and can well be used for training	Kumar et al., 2016 ⁴⁰ ; Chang et al., 2015 ⁴¹ ; Javaid and Haleem 2018 ⁴²
4	Testing and Implementation	- Ensures that the physical model is as per required quality and strength - Under a specific condition of load, it must be feasible & reliable - Testing is essential before actual implementation - Dental model printed by this technology is used during surgery of the patient	Chen et al., 2014 ⁴³ ; Francisco et al., 2016 ⁴⁴

7. Applications of additive manufacturing in dentistry

Applications of AM help dental professional to fabricate any implant and dental devices. Technology can precisely help to improve the daily work of a dentist. It provides development in the medical field, and now it explores its applications in dentistry. Before performing actual surgery, preoperation can also be performed on the 3D model and analysed it. Fig. 2 shows ten major applications of additive manufacturing in dentistry.

In dentistry, AM applications are used to improve patient outcomes. It is used for preoperative planning, education, custom manufacturing and make reliable operation. It produces permanent dentistry implants and devices for the patient.^{75,76}

8. Discussion

Upcoming research & development is towards the production of elaborate dental crowns, aligner, surgical templates, bridges, and orthodontic braces as per requirement of the individual patient. This technology creates an on-demand production of customised dental implants. It has the potential to design & develop tools for dentist and surgeons. AM can help produce complex shaped dental implants/prototype with a wide variety of materials which makes surgeon's job easier with minimum side effects because a 3D printed model gives a better understanding of complex pathology & anatomy of patients which is also suitable for surgical training. Observed there is an improvement in the quality of patient life and efficiently solve different problems in dentistry. Surgeons can now print an implant to practice before the surgery. The dentist can convert need/idea into a reality which provides a comprehensive opportunity to manufacture modified dental implant as per requirement of the patient. It save time for the dental technician and provides improved opportunities to create a new dental product.

9. Future scope

In future, AM can print low-cost, functional dentures using multiple biocompatible materials. It can give a fully printable denture solution. AM is rapidly evolving with new materials. Prosthodontics physical models and any customised, low-cost dental implants seem to be viable. AM technologies can enable collaboration among clinician and laboratory and help to provide a perfect solution for the production of various types of customised medical and dentistry models. The

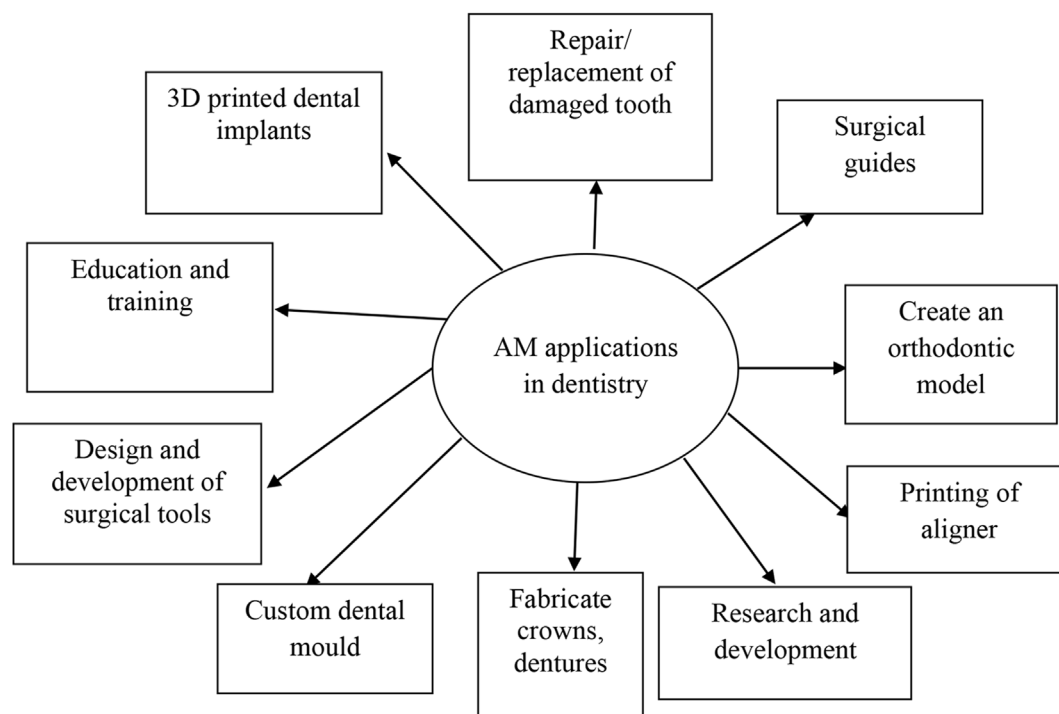


Fig. 2. Major additive manufacturing applications in dentistry.

- **3D printed dental implants:** During dental implant surgery, AM plays an essential role to provide the best solution for creating a template of 3D model which is helpful for the replacement of missing tooth. It improves the accuracy of the surgery as compared to the traditional method. This technique is economical and comfortable in which the dental model gets an excellent surface finish.^{45–48}
- **Repair/replacement of damaged tooth:** Dentist easily scans patient mouth and creates a 3D image of teeth and gums. CAD software helps in the digital design of teeth and print model with the help of AM technologies.^{49–51}
- **Surgical Guides:** This technology produces surgical guides with a high degree of precision. Scanning of patient teeth in CAD form, which is easily printable. It improves the overall reliability of the process and has improved patient outcomes.^{52–55}
- **Create an orthodontic model:** AM easily create a model that is used for the treatment of irregularities in the teeth and jaws. The dentist can now first scan teeth, then design an orthodontic appliance and finally print by AM technologies.^{56,57}
- **Printing of aligner:** Printing of aligner which is the type of braces used for correcting teeth alignment. This technology manufacture customised aligner as per requirement of a patient.^{58,59}
- **Research and Development:** It has a vital role in for research and development of medical and dentistry. By using the 3D scanner and designing software, up-gradation in tools undertaken as per the requirement of the dentist.^{60–62}
- **Fabricate crowns, dentures:** This technology is used to fabricate crown rapidly. Patient teeth are scan and crown is directly printed that save time, and further can also be modified. It prints complete denture with gum and teeth. Multi-material is used to print and all kinds of dental implants and models. It uses explicit material for the printing process.^{63–65}
- **Custom dental mould:** AM has the potential to fabricate customised model. This model can also be used as a mould. Manufacturing of customised and complex geometry implants made in short time with different types of material.^{66–68}
- **Design and development of surgical tools:** It enables efficient design of surgical tools as per the requirement of the dentist. 3D printing drill guides is also possible by this technology.^{69,70}
- **Education and training:** It is important to train medical students for performing various clinical trial and practices. Product manufactured by this technology provide a better demonstration, as model fabricated by this technology is colourful, so it is useful in dentistry for teaching.^{71–74}

potential of this technology is that if any model does not fit, we can make design changes as per requirement and then print it. In future, this technology rapidly will create digital dentistry.

10. Conclusion

Additive manufacturing technologies provide innovation in the manufacturing of complex and mass customised dental implants with negligible wastages. Easy scanning of the Patient-specific dental parts by the dental 3D scanner assists quick printing of personalised dental model with high accuracy. The dentist uses this digital technology for research purpose in which a prototype is created and tested. In upcoming years, this technology will bring a more dental product for a dentistry lab. The dentist can take advantages of this technology for replacement of teeth, crown, braces, dentures, veneers and aligner. Now the dentist can scan the patient mouth, and directly email the

scanned file to the 3D printer lab and hence create a 3D printed model which fits the patient's mouth. It will be quite helpful during complicated cases when different surgical guide models are possible for the surgeon dentist. AM seems to have the potential to solve various problems in this field such as customised requirement, denture positioning and denture retention and improve existing dental implants.

Conflict to interest

None.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jobcr.2019.04.004>.

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