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REVIEW ARTICLE

Perspective of 3D printing in dentistry—Exploring the new horizon

Bharani Krishna Takkella[1*], Nayanala Venkata Anusha[1], Bhavana Sujanamulk[1], Mohammad Naffizuddin[2], Raj Kishore Jammalamadugu[3], Hameeda Pinjari[4], Thakkella Chaitanya Krishna[5], Lokanathan Balaji[6], Mummidi Manasa[7], Vamseedhar Kosuru[8]

[1] *Department of Oral Medicine and Radiology, Drs Sudha & Nageswara Rao Siddhartha Institute of Dental Sciences, Chinaoutapalli, Andhra Pradesh 502355, India. E-mail: bharanikrishna3@gmail.com*

[2] *Department of Oral and Maxillofacial Surgery, Care Dental College and Hospital, Guntur, Andhra Pradesh 522005, India.*

[3] *Department of Pediatric and Preventive Dentistry, Mamata Dental College and Hospital, Khammam, Telangana 507002, India.*

[4] *Department of Periodontics, Mamata Dental College, Khammam, Telangana 507002, India.*

[5] *Teesside University, Middlesbrough, TS1 1AA, UK.*

[6] *Department of Prosthodontics and Crown and Bridge, Priyadarshini Dental College and Hospital, Tiruvallur, Tamil Nadu 602023, India.*

[7] *Department of Oral and Maxillofacial Surgery, Government Dental College and Hospital, Vijayawada, Andhra Pradesh 520004, India.*

[8] *Department of Pediatric and Preventive Dentistry, Narayana Dental College and Hospital, Nellore, Andhra Pradesh 524001, India.*

ABSTRACT

The phrase "3D printing" is frequently used to illustrate a fabrication technique that constructs objects by sequentially adding layers. Additive manufacturing, commonly referred to as rapid prototyping or "solid free-form technology", is a name that more appropriately reflects this method. As a result of the advancement of this technology, 3D objects are converted into 3D photos that are then precisely and perfectly reproduced as required. Using this technique, normal 2D systems are used to visualise 3D objects that are typically seen in radiology. From the perspectives of numerous dental disciplines, including orthodontics, endodontics, prosthodontics, and periodontics, 3D printing technology has been expanding its application in experimental, clinical, and educational sides of medicine and dentistry. It involves innovation and research, training, treatment modalities and education while utilising the swiftly advancing 3D printing technology. It is a promising clinical tool since it makes it possible to see how treatments are working. The use of 3D-printed models in educational programmes encourages students and trainees to practise their dental skills. The improvement of dental education, clinical treatment, and research could all be made possible by the use of 3D printing.

Keywords: 3D Printing; Bio-printing; Additive Manufacturing; Stereolithography (SLA); Selective Laser Sintering (SLS); Scaffolds; Bioinks; Polycaprolactone (PCL); Polylacticacid; Polyglycolicacid; Hydroxyapetite; Tricalcium Phosphate Titanium-implants; Zirconium-implants; Osteointegration; BMP (Bone Morphogenic Protein); CAD (Computer Aided Designing); CAM (Computer Aided Manufacturing); Orthognathic Surgery; Typhodonts; TMJ (Temporomandibular Joint); HPDLMSCs (Human Periodontal Mesenchymal Stem Cells)

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1. Introduction

The technology of 3D printing takes its shape using four steps which are as follows:

(1) Creating a digital 3D model utilising software and data from computed tomography or intraoral imaging.

(2) After processing, a number of two-dimensional levels are produced from the 3D model.

(3) Layer by layer, the 3D item is printed.

(4) Post-processing is performed on the resulting item.

This fundamental process can be used with a variety of printing processes and substrates, including metals, ceramics, and polymers. We examined various Internet assessments that concentrated on particular medical applications, techniques, and methods.

An open manifesto to scientists for aspiring dental surgeons and dentists in the scope of additive manufacturing, 3D printing houses investigational, medical, and future instructional aspects all under one roof.

2. Applications of 3D printing in various branches of Dentistry

2.1 Oral and maxillofacial surgery applications

By enabling more precise diagnosis, clinical 3D imaging using computed tomography (CT) allows enhanced diagnostic and therapeutic planning[1]. Additive manufacturing was used in the discipline of oral and maxillofacial surgery over three decades prior to the creation of anatomical models utilising methods based on CT data. These types of models have since aided in diagnosis, preoperative plotting, portraying as a guide through the surgery, and the development of personalised implantations. By including such additively generated anatomical replicas in their training programmes, future doctors and dentists can take advantage of 3D printing break throughs[2]. 3D-printed individual bones can be used as a form of permanent replacement for maxillofacial prosthesis, for example, additively manufactured condyles can be used as a form of treatment modality after the resection of the condyle in arthroplasty. And full-length bone of the mandible can be additively manufactured and replaced after commando operation and the ideal module of additive manufacturing is visible in severe trauma cases where fully printed craniofacial bones can be used as a customised anatomic implant.

2.1.1 Experimental methods

Bone graft, which employs one of three types of graft sources, is often used in reconstructive surgery.

(1) Autonomous.

(2) Autologous.

(3) Allogeneic.

Allogeneic grafts are thought to be free from size-limitation, ethical, donor-site morbidity and infectious difficulties in contrast to autologous transplants. The development of additive manufacturing has made it possible to create specialised prostheses and supports for tissue and bone regrowth using materials that are biocompatible to treat defects in orofacial, despite the lack of osteogenic and osteoinductive capabilities of these chemicals. As one form of experimental technique, Hixon *et al.*[3] published their research on calcium phosphate biomaterials in 2017. Utilizing three types of graft bases—allogeneic, autologous and autogenously, as well as biocompatible materials for orofacial abnormalities, additive manufacturing has made it possible to develop customised implants and supports like scaffolds for tissue and bone regeneration. By utilising additive manufacturing, the materials that are used for tissue and bone graft regenerative techniques have advanced quickly. These materials now include scaffolds made of polycaprolactone bioactive magnesium-calcium silicate as well as calcium phosphate biomaterials in the forms of polylactic acid, polyglycolic acid, hydroxyapatite, and tricalcium phosphate. Examples of osteoinductive factors that can be included are morphogenetic proteins (BMP2 and BMP7) in bone, which encourage osteogenic differentiation and enhance the integration of bone tissue into printed scaffolds for better vascularization, cell adhesion and proliferation. These scaffolds have undergone cell-free method testing after being seeded with stem cells. Research supporting the manufacture of titanium and zirconium implants has been done in vitro and in vivo. Yet, there are no extensive investigations to assist their therapeutic relevance. It would be fascinating to examine how these compounds influence osseointegration and the recovery process. For the advancement of bone bioprinting, a lot of work has gone into developing workable hydrogels, bio-inks, and inks based on the decellularized matrix. In addition to being biocompatible, these hydrogels have been further functionalized to function as growth factor carriers or gene-activated matrices. An accurate study of the fault with 3D imaging techniques enables a more consistent diagnosis. Splints, implants, contour models, and guides are the four basic kinds of surgical devices that can be three-dimensionally printed. For cranial anatomical models, computer-aided manufacture, and computer-aided design (CAM/CAD) was first used in oral and maxillofacial surgery. Brix and Lambrecht[4] modified a specially designed orthopaedic model created using a milling machine to produce the first anatomical skull models utilising CT data. The ability of milling machines to create complex anatomical structures is limited. Hence, Klein *et al*.[5] described a stereolithography model-making technique in 1992. A maxillary prosthesis was made especially for each patient using that model, as opposed to Lill *et al*.[6] who used a 3D-printed model for preoperative planning of the procedure where allogeneic bone transplantation was used for cranioplasty. Also, the use of 3D printing has made it feasible to thoroughly design and execute surgical reconstruction of maxillomandibular anomalies through the use of 3D virtual operations and immediate prosthesis loading[6]. The surgeon uses 3D software to perform implicitly individualised surgical planning for every case depending on the diagnosis. By familiarising himself or herself with an intraoperative situation using these anatomical models, the surgeon can set up the essential tools and techniques. A fabricated model of the last treatment result can be produced via 3D printing while taking certain treatment objectives into account[7]. This eases the patient to comprehend the surgical approach and visualise the effects of the healing even prior to the surgery. The doctor can employ additive manufacturing to achieve the greatest treatment results and enhance the appearance and quality of life of facial surgery patients. A decisive step in the process of digital surgical planning and implementation is the creation of surgical instructions and models for enhanced precision throughout the operation. They are established on information from a CT scan and analysis from computer software of the abnormalities in maxillomandibular. With the aid of several commercial software programs, it is also possible to create a cutting guide digitally or surgical drilling[8]. It has been shown to be less flawed, to have better margin control, and to experience fewer bone compromises. In the computer, a virtual 3D plan is created and relocated to the machinist site. As a result, it acts as a conduit between the actual patient and the virtual strategy. Orthognathic surgery is another area where 3D printing is used. With these procedures, there is concern about the fossa and condyle of the temporomandibular joint becoming unstable in the long run which is due to the conflict between the actual and virtual strategy of the 3D-printed models and also one drawback of additive manufacturing owing to its concern of lack of actual vascular and neural supply leading to instability over the years[9].

2.1.2 Educational approaches

3D printing, combined with widespread clinical use, is the most useful tool for oral surgery teaching and training. A paradigm shift in training and educational practises is anticipated to occur very soon[10]. 3D printing has tremendous potential to accurately duplicate orofacial anatomy and complex geometry in order to instruct students and professionals on how to perform various maxillofacial procedures. This can be accomplished by employing high-end 3D printers that permit the simultaneous duplication of both hard and soft tissues. These expanded, three-dimensionally printed anatomical representations could potentially assist students learn spatial orientation and improve interactions between doctors and patients[10]. As a result, 3D printing holds a lot of promise for oral and maxillofacial surgery, not presently from a scientific aspect but also from a therapeutic and educational one. Another application is the learning of vital structures through models printed in anatomical layers such as a model based only on bone, a model with muscle, and a model with nerves and blood vessels. Another key application is the usage of models for mock exodontia and impaction surgery procedures; teaching and learning potential is virtually limitless when 3D fabrication is enabled.

2.2 Prosthodontic applications

Reinstating absent teeth has always been a field of continuing progress in dentistry. In the past, materials like stone, gold, wood, silver, and even excised teeth from corpses have been used to replace the missing dentition and other parts of the jaw. In the precedent, alginate or silicone polymers were employed to make intraoral impressions and compression or injection moulding techniques. This surgery is time-onerous, difficult, and demands a highly expert dental technician, especially for patients with gag reflexes, tumour resections, and scarred lips from cancer therapy Kim *et al*.[11], 2017, stated that TMJ issues pertaining to oral deformities could be corrected with high precision with the aid of additive manufacturing. Up to this point, the results of current studies on materials created by additive manufacturing and employed in prosthodontics to create complete and detachable dentures have been encouraging[12]. This silicone prosthesis may now be instantly printed because of advancements in digital workflow, which simultaneously improves aesthetics and reduces the number of patient visits. Researchers and developers in the field of material science may be able to construct new replicas to assess the biocompatibility of new materials by using bio-printing to produce oral tissue replicas[12]. For dental prostheses and crown additive printing, which normally uses metallic and polymer-based materials, ceramics are utilised in 3D printing less commonly than polymers. Ceramics, however, are excellent candidates to be used in stereolithography (SLA) and SLS, in which ceramic powder or a pre-sintered ceramic material is processed to build a structure with strong bonding, due to its special qualities. Minerals that provide calcium and phosphate ions, such as hydroxyapatite and β-tricalcium phosphate, can be added to ceramic structures to provide a friendly milieu. Additionally, it has been demonstrated that the addition of calcium and phosphate mineral phases enhances cell-to-cell communication and promotes cell differentiation and proliferation, making these ceramics suitable for craniofacial applications. However, because it is difficult to convert ceramic powders into high-density structures, the selective laser sintering of these products are porous structures that can be user-friendly[13]. The utmost common 3D printing techniques used today, such as stereolithography, laser sintering, and laser melting, often result in porous materials, but ink-jet printing enables the creation of complex and dense structures that resemble ceramics. To promote uniformity and enhance the mechanical properties of ceramics, porosity should be removed to produce a denser and more compact structure. Further study is required to create ceramics using cutting-edge 3D printing[14].

2.2.1 Clinical techniques

The development of intraoral scanning and 3D printing has made the process of creating dentures more patient-friendly. Published case studies show that removable partial dentures can now be successfully made for patients with lip contractures or small mouth openings. Removable dentures and fixed dentures created using 3D printing are medically adequate and physically equivalent to those created using more conventional techniques[15]. Findings have demonstrated that 3D printing may be utilised successfully for metal implant prostheses by using selective laser melting and electron beam melting. The arduous labour of a dental technician can be reduced by using this advanced technology, which also produces an outline that is more precise than a traditional framework. Metallic crowns and temporary resin restorations have been shown to have equivalent precision and marginal fit to machined refurbishments. As a result, it is obvious that additive printing has a promising future in prosthodontics, especially for people with facial deformities or gag reflexes[15]. The use of computer-aided design and selection of polymeric material with required features for manufacturing, printing, and implantation can be employed to treat dental abnormalities with less time and extremely high efficacy in addition to many other novel applications of restoration and implant prosthesis. The expenses of 3D printing have decreased nowadays due to availability. Additionally, a variety of new materials have been added, and enhanced processes enable integration with various manufacturing systems. As a result, the use of CAD/CAM in dental offices is quickly expanding. With or without the aid of a dental laboratory, adopting digital dentistry can be done in-office for designing and creating various types of surgical guides, restorations, and appliances (such as occlusal splints) using the traditional methods of occlusal appliance manufacture. Occlusal appliances can take a long time to make in conventional laboratory processes, which involve impression materials, transfer jigs, dental stone, cast production, trimming, designing, and finishing. Additionally, this method may result in appliances of varying consistency and quality. Dental implant transfer copings and cast cutting, wax modification, acrylic processing, as well as grinding and polishing, can cause intra- and inter-lab variability. Even if the same technician remakes an appliance for a patient, there will be minor variations from the original design. Using the development of 3D printing, the aforementioned procedure can be simplified using additive manufacturing by employing intraoral cameras to scan the necessary area, then printing the models with great accuracy and precision and shortening the amount of time. Patients must sit in their dental chairs.

2.2.2 Educational approaches

During the earlier years, dental professionals and students have made a remarkable transition from training using optimistic flexible typodonts to more realistic 3D-printed models that are founded on data from patient intra-oral scans. This method has been utilised in prosthodontics to train dentists on customised truthful patient-based models for veneer and crown preparation because teeth in the mouth frequently have fillings or are rotated and twisted. To help students experience the proprioception of working on a real tooth, PolyJet printing has been used to successfully create replicas of strong enamel, cavities, and dentin that are available in a range of hardness levels. Mockup models can be created using the dimensional measurements of patients and thereby creating virtual typos in training the dental students for impression making and placement of implants in bone without causing much damage to the anatomical landmarks and also preserving the bone.

2.3 Applications in orthodontics

By providing specialised, effective, extremely exact, and reproducible conditions in the subject of dentistry, involving orthodontics, 3D printing has transformed the epoch of exactitude medicine. A few years ago, Normando *et al*.[16] proposed the notion of employing 3D face images and 3D printing to produce orthodontic brackets in addition to the structurally accurate and perfect dental arches of patients. Because of this, it is feasible to customise brackets for each patient in terms of angulation, curving, and material choice. It is now able to effectively depict the alterations made by the braces in improvement because of this computer-assisted technology.

2.3.1 Experimental methods

In order to alter inframaxillary growth and tooth movement, individually, basic knowledge of bone biology and cartilage growth is now being tried in animal models. Some of these findings will eventually lead to therapeutic uses in orthodontics for modifying growth, quickening orthodontic tooth movement, and improving anchoring or retention of teeth. Recent research has used CT data collected over the course of a year from an orthodontic patient who was an adolescent to build 3D models of the mandible utilizing medical tomography software. Mandibular growth was examined in the data that were acquired. The outcomes of these investigations were consistent with earlier research using human cadavers and implanted markers. This will help orthodontists understand the growth pattern, paediatric surgeons perform craniofacial surgery, and it will verify theoretical growth models. Complex oral tissue constructs that can be bioprinted can serve to highlight the biological reactions to the stresses created by orthodontic medications. So, these models might serve as an alternative to currently used animal trials[17].

2.3.2 Clinical methods

Orthodontic aligners used to realign teeth are currently produced mostly using 3D printing technology. The patient can remove these aligners at any moment, and they are often only wearing at night time. Salmi *et al.*[18] discussed the potential for using a so-called quick tooling technique to create removable, and personalised regulating splints known as aligners. Patients with mild tooth malpositioning or those who have completed fixed orthodontic treatment can use these aligners for orthodontics. The teeth are digitally positioned in the required location using computer software. The patient-specific casting mould is generated after the 3D model has been displayed. Using the stereolithography printing technique, the mould is constructed layer by layer as it is printed. The orthodontic aligner is afterwards silicone-cast from the completed mould. It also stated how 3D printing was used to create splints for a persistent with temporomandibular joint dysfunction (TMJ) issues. Adults are more likely than children to have TMJ, and those who do tend to have malocclusions like cross-bites[15]. These malocclusions result in painful masticatory muscles and excessive wear and tear on the teeth. More studies and advancements in splint manufacturing are preferred due to the significant occurrence of these dental malalignments[16]. By using rapid prototyping technology, the masticatory muscles' tension can be relieved. Furthermore, by minimising the number of human processes required throughout the process, this method improves precision while saving time and money.

2.3.3 Educational approaches

Since the last ten years, the significance of 3D credentials in orthodontic and craniofacial problems has supported. Digital information and data have now supplanted plaster models in many fields. This not only resolves the bulk storage issues orthodontists frequently have, but it also offers up new avenues for study and research. New theorems and correlations between alveolar area and the necessity for taking out have been established using 3D-printed models, saving the patient from repeatedly being exposed to ionising radiation. In the future, dental students will be able to train in fixed and removable orthodontics using original patient additively produced dental shapes based on intraoral scans or cone beam computed tomography (CBCT)[19].

2.4 Applications in endodontics

As can be observed in the dentistry specialties previously mentioned, 3D printing has also sculpted out a sizable place in the endodontic field. The endodontic paradigm transition from physical to digital workflow has resulted in unparalleled procedural simplification, increased exactness and accurateness, improved patient comfort, an innovation in regenerative endodontics, and the development of operative abilities through education and training.

2.4.1 Experimental methods

The potential of additive manufacturing to conserve the biological tooth rather than replace it through prosthetic surgery has allowed it to infiltrate the field of experimental reformative endodontics. The approach of stem cells, calcium phosphates, pulp scaffolds, injectable, growth hormones, and gene therapy in endodontics can all be accomplished using the 3D printing approaches[19]. By using 3D printing, different kinds of calcium phosphate cements have been created to create porous scaffolds for the regeneration of the pulp-dentin complex. According to research, the osteogenic activity of dental pulp cells when treated in vitro with 3D-printed polycaprolactone covered with freeze-dried platelet-rich plasma is improved. Moreover, anatomically formed tooth-like tissue has been created utilising hydroxyapatite and poly-epsilon-caprolactone scaffolds that were 3D-printed[20]. Moreover, bionics produced from dentin was used to build bioprinting techniques. Dental pulp cell-derived spheroids for scaffold-free methods have demonstrated promising outcomes for regenerative techniques.

2.4.2 Clinical methods

Guided apicectomy and the preparation of the endodontic access cavity are two clinical applications of additive manufacturing in endodontics. The effectiveness and benefits of guided access cavity preparation over the traditional one has been demonstrated in published studies. In cases of calcified canals and apical periodontitis, 3D-printed guides can be a helpful time-saving tool. Endodontic operations are difficult on teeth because of abnormalities in the anatomy of the root canals, making access to cavity preparation, cleaning, and obturation difficult. By creating additively made tooth models with internal root canal features that can be utilised as a base to print a guide for the endodontic treatment of such problematic situations, circulated case studies have demonstrated the possible role of 3D production in this field[20]. As the radiograph only provides 2D knowledge of the root canal, frequently eliminating the auxiliary and lateral canals, this approach can also be used on molars with complicated root canal anatomy.

2.4.3 Educational approaches

The training and education of endodontists heavily relies on additive manufacturing. Typodont teeth, which are known to have principled root canal anatomy, are increasingly being replaced with 3D-printed tooth replicas, which are based on computerized-tomographic pictures of excised teeth with much more realistic anatomic root canal structure, in many dental schools around the world. By giving the user visual, aural and tactile proprioception, 3D-printed models and computer programmes like haptic simulations help with the growth of endodontic skills. Important anatomical features, such as nerves, blood arteries, or thick cortical bone covering root apices, can cause operational errors; in these cases, model scans are a blessing because they help the surgeon get ready for difficult circumstances[21]. As a develop, we can see that both non-surgical and surgical endodontics hold great promise for 3D printing.

2.5 Applications in periodontics

Periodontology is a different branch of dentistry that makes use of 3D printing, with a focus on regenerative periodontology for research and 3D-printed strategies for aesthetic gingival correction. Bone, gingiva, and cementum are only a few of the many parts that make up the complex tissue system known as the periodontium. Because each tissue has a unique set of characteristics, the oral cavity's tissue regeneration is regulated by a variety of cell types, signalling pathways, and relationships.

2.5.1 Experimental approaches

In periodontics, the phrase "additive bio manufacturing" refers to the use of 3D printing to create scaffolds that assist tissue regeneration in a defect. Periodontitis causes tissue and bone loss, and the idea behind this method is to replenish the lost bone and periodontal tissue by gradually introducing growth factors, genetically altered cells, or bioactive substances into the surrounding tissue. Yet, because the residual tissue does not offer enough proof for osseointegration, periodontal tissue degradation can also result in problems after implant implantation or even implant loss. Again, guided tissue regeneration is a technique that makes use of 3D printing. The idea behind controlled tissue regeneration is to leave space for the slow-growing bone tissue to grow while preventing the ingrowth of quickly renewing tissues like the oral epithelium into the gap[22]. Efforts are being made to improve the integrity and functionality of 3D-printed membranes in the oral cavity and increase their resistance to occlusal stresses. Many 3D printing techniques are used in tissue repair, depending on the requirements of the problem location. A CT scan of the patient's defect serves as the model for creating 3D items. The CT image is used to build a printed waxed mould that will serve as a scaffold to encourage the migration of periodontal ligament cells, which are responsible for joining dental cementum and teeth roots. It has been demonstrated that 3D polycaprolactone (PCL) scaffolds improve alveolar tissue regeneration[22]. The development of 3D-printed biphasic scaffolds has made it possible to use and direct several types of periodontal cells throughout the healing process. Biphasic frameworks provide advantages over scaffolds that are manufactured without the exact condition of a printed mould, according to in vivo studies in mice[23]. The employed technique offered predictable direction, enhanced periodontal ligament organisation, and regulated tissue infiltration. Individualized 3D-printed scaffolds have been used in complex clinical instances to support periodontal regeneration. The viability of the approach has been demonstrated in vitro by studies on the bio inks of periodontal cells in hydrogels. Yet, the technology can be used for other things besides tissue engineering techniques. To assess the effects of extracellular matrix in vitro, 3D arrays of biomaterials packed by periodontal stem cells were bioprinted. Such intricate in vitro models can be created as assays for discovering new targets in periodontal regeneration and biomaterials optimization[23]. These cells were known as spheroids of HPDLMSCs. They are more sophisticated microtissues that have been successfully created using periodontal ligament and gingival cells, suggesting that scaffold-free approaches to bioprinting are also conceivable. Such self-assembled building pieces have been suggested for use in periodontal regeneration.

2.5.2 Clinical approaches

Clinically, 3D printing is becoming more common in anterior oral cavity gingival aesthetic operations. For gingivectomy medicines and smile design, patient-specific surgical guides are printed. These prototypes are renowned for their exactitude, adaptability, and accuracy. For the purpose of improving surgical abilities, more and more instructional and teaching models based on computed tomographic scans of individuals are being produced[24]. Advantages over traditional procedures inside the area of periodontal tissue redevelopment and surgery can be achieved via the use of customised products using CAD/CAM designed models[25].

2.5.3 Educational approaches

In the past, periodontal evaluation, counting, and indexing procedures were coached to dentistry scholars whether on manikins, dental simulations, or directly on patients. In probing patients for examination, students have frequently encountered challenges that have caused pain and bleeding in the patients[26]. So, a smart strategy would be to create 3D models of periodontal tissues, gums, and abnormalities with the appropriate tissue properties to simulate each before operating on the patient[27]. The use of printed prototypes for individuals with gingival aesthetic abnormalities for training purposes and error prevention is also encouraged by additive manufacturing.

3. Conclusion

3D printing has revolutionized various branches of science, including medicine. Using various 3D printing techniques, the manufacture of dental objects can be done simply and swiftly without any errors. Additive manufacturing also helps in training purposes to create models for students to train before their hands-on patients at institutional levels with very high efficacy. The multiplicity dentistry offers diverse demands like colour, precision, and detail which can be produced using 3D printing equipment and associated construction materials for purposes like custom implant placement and design, prosthesis, etc. In the near future, additive manufacturing can revolutionise dentistry by taking it to the next level with many intrinsic applications.

Author contributions

Conceptualization, BKT; methodology, NVA and BS; formal analysis, MN; investigation, RKJ and HP; software and validation, TCK; data curation, LB; review and editing, MM; Visualization, VK.

Conflict of interest

The authors declare no conflict of interest.

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