Current perspectives of 3d printing in dental applications

Perspectivas Atuais Da Impressão 3D Em Aplicações Odontológicas

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ABSTRACT

Objective: To evaluate the applications of 3d printing /additive manufacturing (AM) in dental education & clinical dentistry and elaborate various 3d printing technologies, its benefits, limitations and future scope. **Methods:** Research papers on the application of 3d printing in dentistry were searched in Scopus and Pubmed and studied using bibliometric analysis. This review briefly describes various types of 3d printing technologies with their accuracy, use of different materials for 3d printing and their respective dental applications. It also discusses various steps used to create 3D printed dental model using this technology. Furthermore, the application of this technology in dental education and various clinical procedures are discussed. **Results:** 3d printing is an innovative technology making a paradigm shift towards treatment customization. It helps in customized production of dental implants, surgical guides, anatomic models etc. using computer-aided design (CAD) data. This technology coupled with state-of-the-art imaging techniques and CAD software has enabled, especially oral surgeons to precisely plan and execute complex surgeries with relative ease, high accuracy and lesser time. 3d printing is also being utilized in other disciplines of dentistry to prepare aligners, crown and bridge, endodontic guides, periodontal surgery guides, surgical models for treatment planning and patient education. Alongside its possibilities have also been explored in preclinical skills in operative, endodontics etc.

KEYWORDS

3D printing; Additive manufacturing; Dental applications of 3d printing.

RESUMO

Objetivo: Avaliar as aplicações da impressão 3D/ manufatura aditiva (AM) na educação odontológica e odontologia clínica, e elaborar várias tecnologias de impressão 3D, seus benefícios, limitações e escopo futuro. **Métodos:** Artigos de pesquisa sobre a aplicação da impressão 3D em odontologia foram pesquisados no Scopus e no Pubmed e estudados por meio de análise bibliométrica. Esta revisão descreve resumidamente vários tipos de tecnologias de impressão 3D a partir da sua precisão, uso de diferentes materiais para impressão 3D e suas respectivas aplicações odontológicas. Ele também discute várias etapas usadas para criar um modelo dentário 3D impresso usando essa tecnologia. Além disso, a aplicação desta tecnologia na educação odontológica e vários procedimentos clínicos são discutidos. **Resultados:** a impressão 3D é uma tecnologia inovadora que está mudando o paradigma em direção à personalização do tratamento. Ele ajuda na produção personalizada de implantes dentários, guias cirúrgicos, modelos anatômicos etc. usando dados de design auxiliado por computador (CAD). Essa tecnologia, combinada com técnicas de imagem de última geração e software CAD, permitiu, especialmente aos cirurgiões orais, planejar e executar cirurgias complexas com relativa facilidade, alta precisão e menor tempo. A impressão 3D também está sendo utilizada em outras disciplinas da odontologia para preparar alinhadores, coroas e pontes, guias endodônticos, guias de cirurgia periodontal, modelos cirúrgicos para planejamento de tratamento e educação do paciente. Ao lado de suas possibilidades também foram exploradas em habilidades pré-clínicas em cirurgia, endodontia etc.

PALAVRAS-CHAVE

Impressão 3D; Manufatura aditiva; Aplicações odontológicas de impressão 3D.

INTRODUCTION

Healthcare is constantly advancing and shifting more towards better ensemble the needs and requirements for the standard patient care. The progress in medical and dental field especially in imaging techniques has reached a new high. The integration of this recent technology for dentistry has provided for better –quality in serving our patients' need. These advanced technologies in radiology, for examples dental cone beam computed tomography (CBCT) industrial computed tomography (CT) and the medical imaging technique-magnetic resonance imaging (MRI), have led us for better understand of various pathologies. These technologies acquire a three-dimensional (3D) scan image for the targeted section of interest [1]. However, the images in 3D displayed on 2D are not detailed and clear enough to visualize and understand fully the patients anatomical features, here the expert professional rationally recreates a 3D geometrically image produced in the computing machine. Three-dimensional compact items are processed by additive manufacturing technique using computer digital file. For fabrication of 3D printed solid objects additive technique processes are applied. In additive manufacturing process, the required item is created as the material is placed down layer by layer in succession for the creation of an object. Each of these layers can be seen as a thinly sliced horizontal cross-section of the eventual object [2].

Subtractive manufacturing is a process to cut out or tunneling-out plastic or metal piece with milling machine. 3D printing is the opposite of subtractive manufacturing. 3D printing technique allows the operator to produce objects of more complex design and shapes using less material then traditional manufacturing methods.

Charles Hull two decade ago in 1983 was a pioneer for stereolithography- the inception process for 3D printing, then onwards 3D printers were developed and evolved to the present state by numerous manufacturing companies. The advantages of 3D printing are micron accuracy, amazing saving material quantity, complex designing liberty, and adopts tailored or customized fabrication.[3] 3D printing technology, allows specialist doctors individually to customize production of body parts for patients. In addition, 3D models are utilized for planning and practicing surgeries. In dental practice, the applications of 3D printing is utilized in various dentistry branches such as oral surgery for planning surgeries, prosthodontic for fabrication of prosthesis, fabrication of fixed and removable appliances and oral prosthesis, dental implantology and orthodontic appliances etc. [1,4] . In the fabrication process employing additive manufacturing technology, initially 3D image is taken with the help of dental cone beam computed tomography or with medical magnetic resonance imaging, then it is transferred to a software for designing with computer aid so called CAD-the (computer aided design) and finally in the end diverse additive manufacturing technologies are employed for 3D printing [2].

Additive Manufacturing Technology

Standardization is hallmark for quality and according to the ISO-International Standard Organization and American Section of the ASTM-International Association for Testing Materials developed volunteer accord for extensive varieties of products, materials and services in terms of technical standards. There are seven additive manufacturing types as per the committee F42 formed by ASTM for additive manufacturing technologies. The following are the categories: MJ-material jetting, sheet lamination, and direct energy deposition, PBF-powder bed fusion, SLA-stereolithography, or FDM-fused deposition modelling, binder jetting, ME-material extrusion [5].

The present review article emphasis the application of these technologies for dentistry and dental specialties.

• Stereolithography: In this method, the building platform is submerged in liquid resin and the resin is polymerized by the laser source. For each layer formation laser draws a cross-section of the item or object and is then polymerized. The printed object is finally built through this process

with number of times of repetition of the same principle [5]. this technique has twofold benefit , one is the superior exterior surface finishing and two the wastage of resin raw material is reduced to minimal.

• Direct metal laser sintering-DML or SLS-Selective laser sintering: for this technique CO_2 laser beam is used for fusing the resin powder particles, it rises the temperature to melting point of the particles and thus cause powder particles to fuse, thereby forming consecutive layer by layer built-up for the chosen design through CAD. CO_2 laser beam will trace path of the powder bed built on the specified design with CAD. The designed object is finished with repetitive process until completion. Polymers, metals and ceramics are some of the materials utilized with SLS. Whereas sinter metal particles are utilized with DMLS [6].

• DLP-Direct light processing: It is analogous with SLA technology. ASTM considers these techniques as identical to each other. However, light source is the main difference between the two techniques. High-power LED or Digital light projection is utilized as source of light with DLP. The DMD- digital micro-mirror device produces light mask, and the fabricated layers are irradiated with this light mask [6].

• FDM-Fused deposition modeling: For this 3D printing process the thermoplastic material is passed and extruded through the nozzle, here the material is heated and consecutive layers are placed to fabricate a model [2,5-6].

• PJP-Polyjet printing: In this process, Liquid resin is selectively sprayed out through multiple number of nozzles. Here, UV light is used for resin polymerization. As multiple print nozzles are used, there is co-deposition of the supported materials. Furthermore, the materials for buildup with diverse properties and different distinct in color can be selected, and includes formation as well as spatial three dimensional sorted properties [5].

All these 3D printing technologies deal with different types of dental materials and also have different accuracies. The following table1 below illustrate numerous 3D printing techniques, variety of dental materials and the techniques accuracy and their dental applications.

RESEARCH QUESTION

This review addresses the following research questions:

RQ1: To identify relevant research papers on 3d printing applications in all the branches of dentistry through PubMed and studied using bibliometric analysis.

RQ2: To elaborate the process from imaging to 3d printing.

RQ3: To identify significant applications of 3d printing in dental education.

RQ4: To identify significant applications of 3d printing in clinical dentistry.

Table I - Different printing techniques used in dentistry with the materials used, accuracy & their applications in dentistry

Printing Techniques	Accuracy	Material Used	Dental Applications
Fuse deposition modelling (FDM)	30-40 µm	Polylactic acid (PLA), acrylonitrile buta-diene styrene (ABS), Polycarbonate (PC), polyether ether ketone (PEEK) etc.	Simple anatomical models.
Stereolithography (SLA) & Digital Light Processing (DLP)	50-55 µm	Photopolymers, Ceramics Filled resins etc.	Surgical guides, Resin patterns, Temporary restorations, Dental models, Cast coping, Wax pattern splints, Aligners and retainers, Castable crowns, and bridges.
Selective Laser Sintering (SLS)	45-50 µm	Powder such as alumide, polyamide, glass-particle filled polyamide, rubber-like Polyurethane, etc.	Metal crowns, copings and bridges, metal or resin partial denture frameworks
Direct metal laser sintering (DMLS)	20-35 µm	Titanium, cobalt, bronze alloy, aluminum, steel, stainless steel, nickel alloy.	Metal coping and framework
Polyjet printing	20-85 µm	Photopolymers	Facial prosthesis, surgical guides, craniomaxillofacial implants, anatomical models etc.

1. Research status of 3d printing in various dental disciplines

The research articles related to this area were searched in PubMed database till April 2020 by keywords as "3D printing", "additive manufacturing", "oral and maxillofacial surgery" "prosthetic dentistry", "endodontics," "orthodontics", "restorative dentistry", "pedodontics" "periodontics". Selection criteria included English language, study articles regarding application of 3D in dentistry and in all dental specialties from 1995 to April 2020. In all 1437, total articles recognized and all relevant articles were shortlisted. From the data, we observed that the first article published in 2006 and there has been an increase in the number of publications since then (Figure 1). The graph shows number of publications in all the disciplines in dentistry from 2006 to April 2020. The results from the literature search revealed that the maximum number of publications were in oral and maxillofacial surgery (444), followed by prosthetic dentistry with (320), orthodontics (130), endodontics (56), restorative (50), periodontics (19) and pedodontics (16). The highest number of research articles were from United States of America followed by a substantial number from China and Germany.
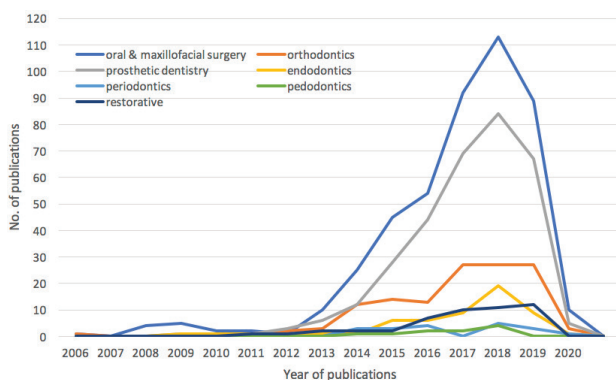

Figure 1 - Number of publications year wise from 2006 – April 2020 in different disciplines in dentistry.

2. Process from imaging to 3d printing

There are three major steps in 3d printing physical models or surgical guides. To start, initially, a virtual model is designed. From the image data obtained from CBCT, MRI or CT the desired model generated on a computer. After sophisticated refinement of the models, an error free file created. Thereafter finally, the refined model data sets exported to 3D printers to fabricate the desired physical models. Required materials are selected appropriately and carefully the printer settings adjusted to obtain a superior quality 3D printed model [7]. Figure 2 represents the major stages summarizing the 3D printing process.
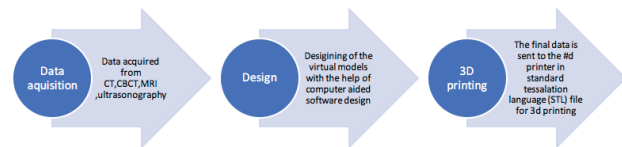
Figure 2 - Process from imaging to 3d printing.

3. Applications of 3D printing in Dental Education

With digital imaging and scanning coupled with powerful software tools and 3D printing there will be a drastic change in training pattern as well as educational standard protocols globally. Three-dimensional printing allows duplicating of orofacial anatomy with high precision. Highly sophisticated 3D printers are capable to replicate, in one jaw, both hard and soft tissues, which will be useful for training purpose [8,9].

3.1 Oral Surgery: The dental students and residents in oral & maxillofacial surgery can have a complete understanding of the head & neck region and their spatial relationship through 3d printed anatomic models [10,11]. Siefert et al. [12] and Chen et al. [13] in their study of comparing 3D printed models with cadaveric models in anatomical education conclude that these models are lifelike alternative models probably replacing cadaver models to train and develop surgical skills for dental students in oral maxillofacial surgery. Lioufas et al. [14] for surgical training and education utilized 3D printed models for cleft palate pathology. Moreover, haptic model that are 3D printed are low cost-effective that will provide efficient education and training for undergraduate

students in craniofacial traumatology. Highly accurate anatomic prototype 3d printed models help the surgeons to scrutinize the anatomy and training for different techniques so as to decrease operating time, avoid procedural mishaps, and improve surgical outcomes [15-17] . The models can also be used to design and fabricate tailor-made prostheses, bone grafts of required sizes and allow scaffolds fabrication for bone regeneration [18].

3.2 Prosthetic Dentistry: 3D printed teeth are now commonly used for teaching preclinical dental students in preclinical fixed prosthodontics. Training for dentist can be imparted by utilizing this idea with real patient based custom-made models for crown and veneer preparation, to avoid rotated and filled teeth as present in the oral cavity, in prosthodontic dentistry[19]. The 3D-printed teeth are cheaper than the commonly used stone tooth models, and are excellent for learning as well as teaching models. Furthermore, the 3D printed teeth duplicates measurement of the ideal or perfect tooth preparation [4]. Hohne et al. [20] designed 3D printed teeth that mimic enamel and dentin crown layers that are encountered during crown preparation and are excellent for educational purpose.

3.3 Orthodontics: In orthodontic and craniofacial disorders, 3D documentation is highly recommended since last 10 to 15 years because of its significance. Digital 3D printed models are gradually replacing conventional plaster models. In near course of time dental models of real patients will be utilized for fixed and removable orthodontics educational training to dental students [8].

3.4 Endodontics: Endodontic training and education is being influenced by rapid prototyping. Across the globe endodontic training of dental graduates was traditionally done on typodont teeth with ideal root canal anatomy or on extracted teeth. However, studies have been undertaken to explore the possibility of using 3D printed tooth models based on scan from patients obtained with dental cone beam computed

tomography,[19,21] achieved good results. 3D printed models created before surgery called as pre-surgical models, for surgical endodontic [22]. these innovation develops harmonization and coordination between students and tutor, similarly it allows acquaintance to difficulties that may be occur during patient treatment, such as difficult bony prominence, complicated root morphology, difficult root curves and proximity to nerve bundle and other important reginal structures. Thus models prepared with 3D printing are very useful for teaching students in endodontics, as well as it increases perception of normal or complex canal anatomies, root types and tooth morphology and various canal preparation technical steps such as access cavity preparation, cleaning-shaping of the root canal can be simulated[23]. Robberecht et al.[24] developed root canal model that was duplicable, bio-imitating for education and training purpose in preclinical as well as for post graduates in endodontology. Kfir et al. [25] demonstrated for preclinical work all the steps in simulated root canal treatment- perfect access cavity, canal cleaning and shaping and the canal obturation can be performed on three types of den invaginatus with clear acrylic/plastic tooth.

3.5 Periodontics: Earlier in periodontology undergraduates used plaster models, phantom head, or straight on the patients for intraoral examination, recording scores or disease index recording procedure [26]. It remains to be seen if 3d models can be printed simulating the periodontal tissues with proprioception to be used in training . Li et al.[27] printed models of patients with gingival esthetic defects for presurgical simulation .

3.6 Restorative Dentistry: In the preclinical phase rapid prototyping models of different cavity preparations can help students visual¬ize tooth structural configuration and elusive alterations in the cavity preparations [28].

3.7 Pediatric Dentistry: Marty et al. [29] in the year 2019 developed 3D printed models with simulation of caries to perform pulpotomy

and fabrication of stainless steel crown. As the models are actually made from patients radiographs dental students can visualize the factual pathology in terms of size, extent and deepness of the decayed lesion and in addition it will provide morphological complexities and specific tooth variation. Therefore, it will make possible to alter the models, by the teacher, as per the educational objectives.

4. Applications of 3D Printing in Clinical Dentistry:

4.1 Oral Surgery: The main clinical indications of 3D printing are surgical guides, contour models, occlusal splints & implants [8].

4.1.1: Surgical Guides: They are used for dental implant surgery, mandibular & maxillofacial reconstruction, orthognathic surgery, TMJ surgery.

With the advent of 3D printing, guided surgery is becoming increasingly popular. They help in preoperative planning for correct implant placement. Van assche et al.[30] in a literature review study stated 0.99mm of average error at the entry point and of 1.24mm at the tip and the average of 3.81°angular deviation of guided implants. Surgical guides have been successfully used for almost all types of implant surgeries ranging from single tooth [31] to sinus lift [32], full mouth [33] zygomatic implants [32] . Surgical guides are also utilized in mandibular and maxillofacial surgeries. They are cutting guides, drilling guides and positioning guides. Cutting guides help in accurate placement and angulation of osteotomy lines. Drilling guides help in inserting the screws at the predetermined locations and positioning guides positioning for the osteotomized bone segments according to the surgical-planning [34]. The use of guided surgery reduces the surgical time-span and improves the clinical and esthetic outcomes[35].

4.1.2 Contour Modelling: Contour models are 3d printed models of patient-specific anatomy. Contour models represent the positive-space models where the patient's imaged anatomy is the 3-D printed object for preoperative training on the model and for

pre-shaping/ pre-bending osteosynthesis or reconstruction plates according to the planned outcome [34,35] .

4.1.3 Occlusal Splints: When performing the jawbone surgery for aligning the masticatory apparatus teeth occlusion in its proper position, splints are placed in the corrected positions in the patients mouth as these occlusal splints replicates the resultant post-surgical location for the oral occlusion in the patients' mouth. This requires an innovative 3D designing computer-software simulated surgery to do concluding condition [35].

4.1.4 Implants: Patient specific implants (PSI) are used in repairing defects in cranio maxillofacial defects related to tumors, traumas, infections, or congenital deformities. These implants are made of polymers, metal-titanium and other various biocompatible material [34,35]. In oral surgery, it is possible to make a custom-made patient specific implants. This innovative technique is in use since several years for reconstruction of temporo-mandibular joint and is recently being utilized for rehabilitation in surgical orthodontia [36].

For three-dimensional reconstruction of skeletal-frames the contra-lateral (fit) side is obtained by a technique called as- mirroring. The primary benefit from this procedure is symmetrical replication, simple to use, very accurate and predictableness of post-surgical outcome. Moreover, not only the hard-tissue but also the soft-tissues can be planned for replacement [34].

In addition, 3D customized root-shaped implants are developed. These implants were the products German company at Berlin. Made up of metal-titanium, it is a minimal-invasive implant mimicking original root shape, tailored as per patient requirement [37].

4.2 Prosthetic Dentistry: The applications of 3d printing has resulted in a paradigm shift in prosthetic dentistry. A partial or fixed removable denture can be made hassle free with a complete digital workflow involving scanning and printing. These digital dentures have

comparable physical properties to conventional dentures. Fabrication of metal framework of removable partial dentures achieves excellent fitting and is replicated with ease. Moreover, intrinsic faults are eliminated, associate with the laboratory fabrication procedure [38].

Metallic full crowns and temporary acrylic crowns showed precision and good margin fitting comparted to the machined crowns [39,40].

Fabrication of custom trays, wax pattern for prosthetic constructions , fabrication of all ceramic restorations are the other applications in prosthetics [41].

4.3 Orthodontia: More recently 3D printing technological application more commonly used in orthodontia. Orthodontic appliance are fabricated using CAD CAMs, mouth scan and, CBCT [42].

With the advent of three dimensional printing, aligning ortho-appliances are employed for the correction of crowded teeth [43].

Fabrication of occlusal splints utilizing 3D printing technique for the mandibular joint disorder has been reported by Salmi et al. (2013) [44].

Another aspect of orthodontics that benefits from 3D printing- is manufacturing of orthodontic braces. The brackets are custom built and tailored to individual tooth surfaces. They can be accurately positioned using 3D printed guides[45]. Liu et al. [3]constructed and 3d printed a personalized arch wire groove model, to assist in giving individual customized shape for the arch wire with ease and swiftly, thereby enhancing the effectiveness and perfect arch wire manipulation and bending.

Additive manufacturing   also enables fabrication of various orthodontic devices such as mouth guards, retainers, expanders, sleep apnea appliances etc.; providing better intraoral adaptation [8,46].

4.4 Endodontics: Clinically, additive manufacturing in endodontics is founded on designing and creation following the same doctrine as for implants in guided surgeries. This technology is effectively used for guided-access cavity, guide root canal treatment and for endo guided-surgical procedures [23]. Scientific study reported benefits and its effectiveness of guided- root canal access when compared with the routine conservative access cavity preparation. For apical root canal lesions and calcified root canals endodontic access guided 3D printed stents are of great advantage [47].

These access guide stent provide proper direction toward the obliterated root canal during conventional root canal treatment. This will minimize the danger of endodontic mishaps such as misdirected bur and the canal perforations that can potentially hamper the success for the root canal therapy. There are clinical reports supporting the use of 3D printed access guided for the calcified obliterated root canals and for anterior teeth anomalies like Den invaginatus, for locating the hidden root canals during conventional endodontic therapy [8,48]. Surgical guides for apicectomy have been successfully used in endodontic surgical procedures [47].

4.5 Periodontics: Clinically, surgical guides are used for   aesthetic periodontal surgery in esthetic zone [27].

For accurate and precise treatment results for gingival surgeries, custom-made surgical 3D printed guides have been employed in dental practice. 3D printing technology in being applied in regenerative periodontology. Studies are being done to evaluate the use of 3D printed biphasic scaffolds to help in tissue regeneration of defects and in healing process[8,46].

4.6 Restorative Dentistry: Studies have evaluated the accuracy & fit of intra coronal restorations fabricated by 3d printing comparing with conventional methods have yielded good results [50,51].

Limitation and future perspectives

3D printing is revolutionizing dentistry in all the disciplines. This technology is being

embraced globally by the dentists because of the availability of low cost yet accurate 3d printers, there is in house production of dentures, crowns, orthodontic aligners, various surgical guides for planning and treatment. However, a learning curve is essential for the dentist and the dental personnel. In future, the research will explore more about the mechanical strengths, biocompatibility, accuracy and reproducibility for printing materials. It includes technical features on the surface details, proper and exact shape and size for the fabricated portions. Hence, further research focus is on expansion of printable materials used in dentistry.

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