REVIEW

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The Use of Additive Manufacturing Technologies in Restorative Dentistry

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Abstract

In today's era, as in many other industries, there has been a rapid trend towards digitalization in dentistry with the use of computer-aided design and computer-aided manufacturing (CAD/CAM) technologies becoming increasingly common. In dentistry, three different concepts are used to produce a physical prototype: additive, subtractive and hybrid. Additive manufacturing techniques, which serve on the basis of CAD/CAM technology, have been shown to be an alternative to subtractive methods with the various advantages they offer, and for this reason, their use in the dental industry has increased rapidly. It is predicted that additive manufacturing technologies, which have found a wide range of uses in various dental applications, will become the main method for digital manufacturing in dentistry in the future. In this review, it was aimed to examine the CAM methods which are commonly used in dentistry; to evaluate the advantages and disadvantages of these methods systematically; to examine the functioning processes of additive manufacturing technologies which are used in dentistry; and to evaluate the uses and developments of these additive manufacturing techniques in restorative dentistry. For this purpose, a literature scan was conducted using MeSH terms related to the subject ("manufacturing, fabrication techniques", "CAD/CAM, restorations", "digital dentistry", "additive, subtractive systems", "additive manufacturing in restorative dentistry") in medical databases (Medline- PubMed, Embase).

Keywords: 3D printing, additive manufacturing, CAD/CAM, digital dentistry, subtractive manufacturing

INTRODUCTION

Computer-aided design and computer-aided manufacturing (CAD/CAM) applications have proliferated in dentistry as a result of rising technological advancements in this field (Figure 1, 2). These applications are popular due to benefits such as enabling the creation and use of new materials, requiring less labor, being cost-effective, and having control over quality.[1] The concept of using CAD/CAM methodologies to complete indirect restorations made of a material with superior biological and mechanical qualities in a single session and to deliver them to the patient marked the beginning of indirect restoration applications.[2] In CAD/CAM applications, there are three different manufacturing strategies: subtractive, additive, and hybrid.[3-5] Due to its ability to generate more complex, sophisticated structures with reduced material waste, additive manufacturing is now being employed as a substitute for subtractive methods in dentistry.[6,7]

The aim of this article was to give information about three-dimensional (3D) printing technologies which are used in dentistry and to examine the application areas of these technologies in the field of restorative dentistry.

CAD/CAM Technologies

All CAD/CAM systems, past and present, essentially provide services based on three functional components.[8] The first part scans the area which the dentist has prepared either intraorally or extraorally and gathers data about the pertinent region. The restoration can be planned and developed in three dimensions on a computer thanks to the second component, CAD. The final element, CAM, makes it possible to produce the restoration which has been virtually prepared.[9] In general, CAD/CAM systems are split into "*Open*" and "*Closed*" systems based on their ability to share digital data.[10] All CAD/CAM processes, including data

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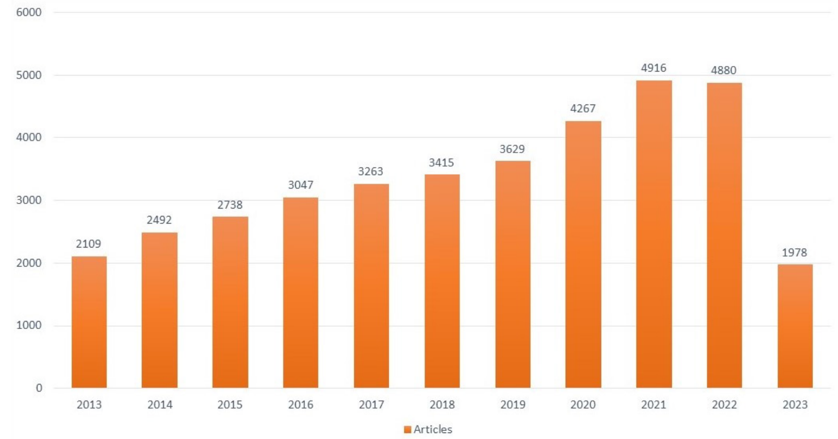

Figure 1. Year-wise (2013-2023) literature production in the dentistry field on additive manufacturing technology.

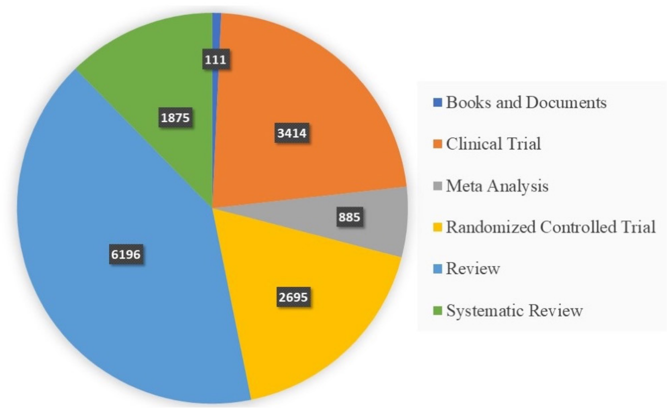

Figure 2. The ratio of the types of articles published on additive manufacturing technology in the field of dentistry.

collection, virtual design, and restoration manufacturing, are included in closed systems; however, data sharing between these systems and other software and hardware is not possible. Closed systems have this drawback, while open systems enable the original digital data produced on a particular device to be read and processed by many CAD software and CAM machines.[9]

Subtractive Manufacturing Technologies

The premise behind the subtractive manufacturing process is that the final product is milled from pre-fabricated disks or blocks composed of certain materials.[11,12] This method has certain drawbacks even though it can successfully achieve a final restoration. 90% of the block is used, and 10% is wasted with no chance of recycling.[13,14] In addition, the milling components used in this system are exposed to heavy abrasion,[15] the production system is insufficient for the production of complex shapes,[4] and also shrinkage and fractures can be seen in the material.[16] Due to the existing disadvantages of this method and the rapid developments in additive manufacturing, the use of additive manufacturing techniques in dentistry has been brought to the fore and studies on this subject have gained importance today.

Additive Manufacturing Technologies

Systems that enable the fabrication of a 3D-designed object by integrating layers on layers with computer assistance are known as additive manufacturing systems. Additionally, the American Society for Testing and Materials describes additive manufacturing as "*the process of combining materials by layering (adding layer upon layer) to produce objects from computer data of a 3D model, in contrast to subtractive manufacturing methods*."[5,17]

In addition to being known as 3D printing, additive fabrication, fast prototyping, rapid manufacturing, freeform manufacturing, layered manufacturing, and solid freeform fabrication, additive manufacturing technology has become a common practice in dentistry today.[18]

In contrast to subtractive manufacturing, which creates solid materials by milling, additive manufacturing involves layering powder or liquid based ingredients to create solid objects.[12,19] While other techniques use inkjet printing nozzles to spray the binder or solvent onto the powdered ceramic or polymer, some methods use thermal energy from optically directed laser or electron beams to melt or sinter metal or plastic powders together.[12,20]

Two different types of materials, build materials and support materials, are typically deposited in an additive manufacturing device. The support material is not a component of the finished product, but it is required to support the build material placed in voids and overhangs.[21] Despite the fact that many different additive manufacturing processes build and combine layers in a variety of ways, each methodology essentially comprises three steps.[22]

These are;

1. Creating a 3D design in a computing environment and converting it into a traditional additive manufacturing programming language or current additive manufacturing file format.

2. Transmitting the generated design file to a device that uses additive manufacturing technology to make adjustments such as positioning, adjustment and sizing of the object to be produced.

3. Layer-by-layer manufacturing of the designed object.

Vat Polymerization Techniques

Vat photopolymerization is an additive manufacturing process which uses light-activated polymerization to selectively polymerize a liquid photopolymer in a vat. Vat polymerization is a process used in additive manufacturing technologies such as stereolithography (SLA), digital light processing (DLP), continuous liquid interface production, and multiphoton polymerization (MPP).[22]

Stereolithography: SLA is based on the concept of photopolymerization, where monomers form polymeric structures through photons supplied from a ultraviolet (UV) light source.[20,23] It is the process of producing geometric cross-sections imported into software on a light-cured resin surface by means of a laser light source controlled by mirrors.[22]

Digital light processing: DLP is based on the principle of layer-by-layer production by the selective curing of a light-cured resin by a light source, similar to SLA. DLP is also called dynamic mask photolithography because it is very similar to SLA. In contrast to SLA, the light source simultaneously polymerizes the resin in each layer of the object being produced. In addition, this technology uses a production direction opposite to SLA.[21]

Continuous liquid interface production: The working principle is very similar to conventional DLP. The difference is that it uses an oxygen-permeable film to inhibit polymerization on the surface close to the UV source and consequently eliminates the need for an intermediate coating step for each layer.[21]

Multiphoton polymerization: The term "multiphoton" recognizes that the simultaneous absorption of three or more photons can occur (although with very low probability) and photopolymerization will be achieved. With the production of powerful and high-tech lasers, this technique has become feasible. However, the production time and the size of the object which can be produced are still not at the desired level (production size is limited to 30x30 µm).[24] In contrast to traditional SLA, MPP is the process of producing the entire desired object at one time by MPP without using the layer-on-layer technique. Thus, complex structures which cannot be produced in SLA can be produced.[21]

Material Extrusion Methods

Material extrusion is an additive manufacturing technique in which material is selectively distributed through a nozzle.

Fused deposition modeling: This is the most commonly used printer technology for model manufacturing. In this technique, the production employs the method of forming layers with melted thermoplastic filaments.[25] Wax, metals and ceramics are the main materials used in this technique.

Inkjet Printers

In this technique, production is carried out by selective deposition of droplets of photopolymer or thermoplastic materials.[26]

Thermal inkjet printing: The term thermal inkjet printer refers to the spraying of liquid phase materials and/or inks consisting of material dissolved or dispersed in a fixed amount of solvent material in the chamber from the nozzle in the form of droplets which depend on the pressure of air bubbles which form due to the increase in temperature. The piezoelectric effect can also be used to eliminate the need for solvent.[21]

Inkjet-based lithography: Also known as polyjet photopolymerization or multijet modeling, this technique combines the advantages of lithographic methods such as high resolution and good surface quality with the advantages of inkjet methods such as high production speed and large volume object production.[21] In this technique, photopolymerizing resin droplets are sprayed onto a platform by hundreds of nozzles and the layer formed is polymerized with a UV light source.[27]

Aerosol Jet Printers

Aerosol jet printers were patented and commercialized (Optomec Inc.) in 2004. In this technique, droplets of the material used in production with a diameter not exceeding 1-5 µm are sprayed with ultrasonic energy (1.6-2.4 MHz) or pneumatic atomization.[21]

3D Printers

3D printers (3DP) utilize a technology similar to inkjet printers and they provide object production by spraying particles of the powdered base material in the production platform onto a binder molecule surface.[11]

Powder Bed Fusion

This method melts and fuses powdered particles onto a production platform using thermal energy produced by a laser or electron source.[28] There are now three different powder bed fusion (PBF) technology types: electron beam melting (EBM), selective laser melting (SLM), and selective laser sintering (SLS). There are differences between these three PBF techniques in terms of factors such as melting temperature, energy source, energy power, thermal conductivity, room conditions, temperature to be reached, layer thickness, structure orientation, and particles.[19]

Selective laser sintering: This technique uses laser energy from carbon dioxide (CO_2) and neodymium-doped yttrium aluminum garnet lasers to fuse plastic, ceramic or glass particles.

Selective laser melting: The SLM technique can be considered a variation derived from SLS as the same steps are applied in both techniques, but the main difference is that SLM completely melts the powdered particles with the powerful laser beam to create fully dense metallic models.[29] The most common laser used in SLM technology is the CO_2 laser.[19,30]

Electron beam melting: Selective EBM is an additive manufacturing technique used in the production of metal components. This technology, which was first marketed in 2006, produces an object by melting a metal layer by layer using electron beams in a high vacuum.[29] EBM has the ability to process brittle materials which generally cannot be processed by SLM.[31]

Rapid Freeze Prototyping

Rapid freeze prototyping produces dental restorations using ice molds instead of traditional wax molds. This technique is a new and environmentally friendly solid free-forming process which can selectively deposit a water layer and then rapidly freeze it, producing a 3D ice model based on a CAD model.[11]

Laser Engineered Net Shaping

Laser engineered net shaping is also called laser metal deposition or laser coating. The powder is completely melted by a powerful laser beam, similar to the SLM technique, but in this technique, the powdered particles to be melted are sprayed by a nozzle.

4D Printers

Unlike 3DP, which manufacture static materials which maintain the same shape and properties throughout their lifetime, 4D printers (4DP) aim to manufacture dynamic models whose properties and functions can change depending on external stimuli such as heat, pH, humidity, light, pressure, touch-shear and electromagnetic radiation.[5,21] The manufacturing of these dynamic models is carried out by digital modelling designed with special software which can calculate the shape and dimensional changes which may occur.[5,32]

Hybrid Manufacturing Technologies

Hybrid systems combine the versatility of additive manufacturing with the advantages of subtractive manufacturing.[33] There are a limited number of CAD/CAM systems which incorporate both additive and subtractive manufacturing approaches. Commercial examples of these manufacturing approaches are Procera (Nobel Bio-Care, Gothenburg, Sweden) and Wol-Ceram (Wol-Dent, Ludwigshafen, Germany).[3] In addition, although laminated object manufacturing is classified within additive manufacturing systems, it is actually a system which works with a hybrid approach, but since the additive manufacturing part is highly dominant, it is usually mentioned among the additive manufacturing techniques.[11]

Additive Manufacturing Technologies in Restorative Dentistry

The use of additive manufacturing techniques in dental applications is increasing day by day. These technologies are preferred in many applications especially in the prosthetic (temporary or permanent crown/bridge, framework, model production, etc.), surgical, endodontic, restorative (guide formation) and orthodontic (model and personal appliance production) fields.[7,34,35] In addition, additive manufacturing techniques are emerging as a preferred technology in regenerative applications (especially in scaffold production) in parallel with the development of dental materials and innovations in tissue engineering.[25,36,37]

Digital Wax-up and Guide Design in Anterior Restorations

In cases regarding the high aesthetic expectations of patients in the anterior region, the deficiencies in patient-doctor communication, and patient concerns about the appearance to be obtained at the end of the procedure, mock-ups, wax-ups and guide applications may be preferred in order to create appropriate forms, sizes, contact relationships and to ensure that the patient and dentist are on the same page before direct restorative procedures are started.[38]

In digital technology, the ability to instantly transfer intraoral scans to the computer environment and to superimpose these data with the patient's facial photographs or 3D facial scans by means of CAM design software has made digital wax-up applications frequently preferred in the design step of the planned restorations (Figure 3).[39]

This development provides very fast feedback on any changes in the design plan instead of the traditional intraoral mock-up or wax-up methods used on the model in aesthetic services such as smile design.[40] In addition to wax-ups created in digital format, dentists and technicians can use natural shapes from digital libraries and adapt them in a very short time, unlike traditional wax-ups. Thus, the digital wax-up can be readjusted easily and efficiently, and the proposed design can be created without compromising aesthetics and/or periodontal health.[39]

The introduction of 3D printing technology in this field has brought many advantages. Thanks to additive manufacturing technologies, a model can be obtained from digitally prepared wax-up designs and consultation with the patient can take place, and if desired, silicone mock-ups can be prepared on this model (Figure 4).[38]

Recently, this technology has enabled the development of 3D printed rigid preparation guides with a new design which makes it possible to overcome some of the limitations of silicone indexes and improves the ability to visualize the teeth. Furthermore, in the multidisciplinary treatment protocol of aesthetic anterior restorations, it has become possible to 3D print crown lengthening guides which can be used in the periodontal surgery step in order to improve facial aesthetics by restoring the harmony between hard and soft tissues.[38,39]

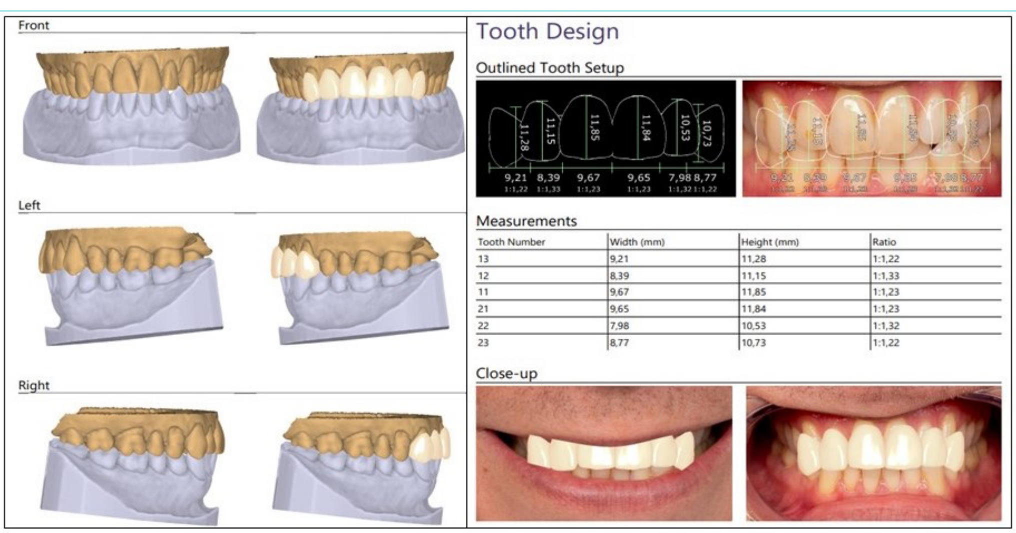

Figure 3. Digital wax-up design in the anterior region using CAM design software.

CAM: Computer-aided manufacturing.

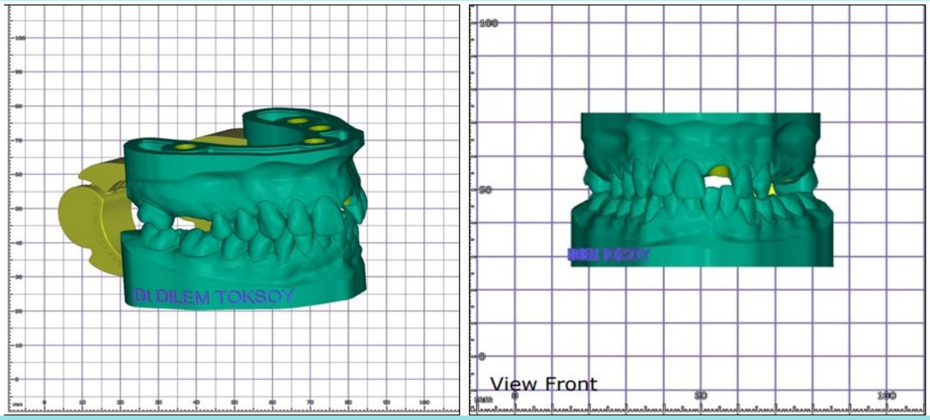

Figure 4. 3D printed model design.

3D: Three-dimensional.

Additionally, after the periodontal and surgical procedures are performed, resin shells produced with 3D printing technologies can be adapted to the patient's mouth as post-operative mock-ups and the patient can have precise information about the final restoration shape.[39]

Indirect Temporary Dental Restorations

Temporary dental restorations, which are important not only for the protection of pulpal and periodontal tissues but also for oral function and aesthetics, have recently started to be produced with CAD/CAM technology as an alternative to conventional methods.[23] Most commercially available dental CAD/CAM systems utilize the milling method in which temporary crowns are mechanically shaped from a resin block.[12] While the strength and accuracy of temporary crowns are higher than those fabricated with the conventional direct technique because the resin block is polymerized with a high degree of conversion in this fabrication technique; the range of motion of the fabrication device and the size of the milling burs are the main disadvantages as they limit the shape which can be milled.[4,41] In order to eliminate such disadvantages of subtractive methods, additive manufacturing techniques have also been used in the production of temporary dental restorations.[23,42,43] Temporary dental restorations produced with additive technologies are becoming the preferred choice of many clinicians because they have sufficient mechanical strength, exhibit superior internal/marginal fit, and can be easily produced with SLA-based 3DP.[44] However, additional research is needed on the biocompatibility and long-term outcomes of the polymers used in additive manufacturing (Figure 5).[22]

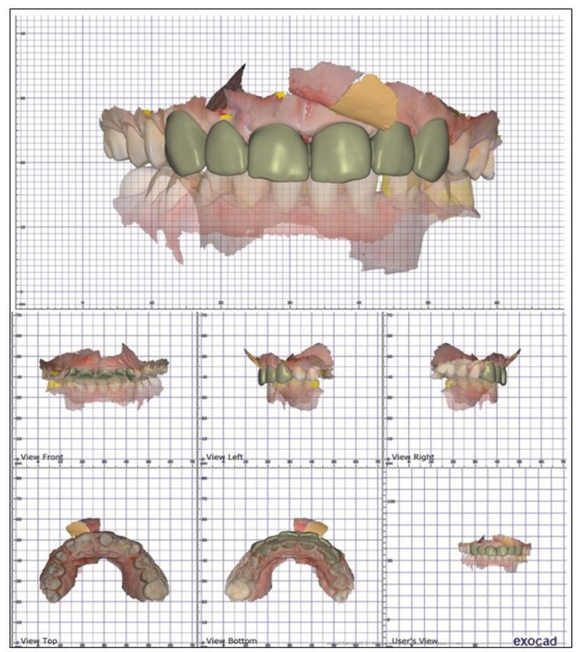

Figure 5. Anterior temporary restoration designed for manufacturing on a 3D printer.

3D: Three-dimensional.

Fabrication of Indirect Dental Restorations

Nowadays, 3D printed hybrid composite resins developed by different brands are available for use in permanent restorations. In the indirect fabrication of permanent restorations with additive manufacturing technology, firstly, the relevant tooth is prepared in accordance with the minimum thickness values for the restoration reported by the manufacturer and after scanning with an intraoral scanner, the virtual design of the restoration is made and sent to the relevant production unit in STL format (Figure 6). After the manufacturing and post-manufacturing processes are carried out, the restoration is cemented onto the abutment tooth with the appropriate adhesive system and luting cement in accordance with the manufacturer's instructions.[45] Although the additive manufacturing of hybrid composite resins seems promising in terms of the advantages they offer to the laboratory, clinicians and patients, more studies are needed to compare these materials with those materials used in conventional and subtractive methods.[46] The 3D printed hybrid composite resins of some of the different brands available on the market for use in permanent restorations are shown in Table 1.

Regenerative Applications and Tissue Engineering

As dental tissues have complex structures, anisotropic mechanical properties and heterogeneous cell distribution, it is difficult to mimic their complex 3D structures by using conventional techniques. Recently, the 3D bio-printing of dental and craniofacial tissues has been proposed

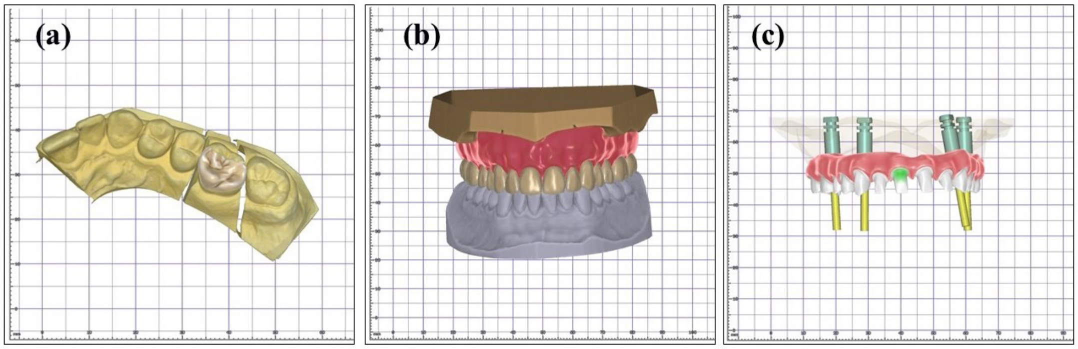

Figure 6. Onlay restoration designed for fabrication with 3D printable hybrid composite resins (a), total prosthesis designed for fabrication with 3D printable hybrid composite resins (b), implant supported prosthesis designed for fabrication with 3D printable hybrid composite resins (c).

3D: Three-dimensional.

Table 1. Commercial names of 3D printable hybrid composite resins available on the dental market and the composition, flexural strength, indications, shades and manufacturing technologies of these materials

Name	Composition	Flexural strength	Indications	Shades	Manufacturing technology	Manufacturer
Varseosmile Crown[plus]	Silanized dental glass, methyl benzoylformate, diphenyl(2,4,6-trimethylbenzoyl) phosphine oxide, 4.4'-isopropylidiphenol, ethoxylated and 2-methylprop-2enoic acid, inorganic fillers	116-150 MPa	Single crowns, inlays, onlays, and veneers	A1, A2, A3, B1, B3, C2, D3, BL	DLP	BEGO GmbH & Co. Bremen, Germany
SprintRay Crown	Silanized dental glass, methyl benzoylformate, diphenyl(2,4,6-trimethylbenzoyl) phosphine oxide, 4.4'-isopropylidiphenol, ethoxylated and 2-methylprop-2enoic acid, inorganic fillers	>100 MPa	Single crowns, inlays, onlays, and veneers	A1, A2, A3, B1, B3, C2, D3	DLP	BEGO GmbH & Co. Bremen, Germany
SprintRay Ceramic Crown	Oligomers, monomers, photoinitiators, additives	136 MPa	Single crowns, inlays, onlays, and veneers, artificial teeth for dental prostheses	A1, A2, A3, B1, B3, C2, D3, BL	DLP	SprintRay Inc., Los Angeles, USA
Saremco Print-Crowntec	Bisphenol a polyethylene glycol diether dimetaacrylate, BiSemA, methyl benzoylformate, diphenyl(2,4,6-trimethylbenzoyl) phosphine oxide	>135 MPa	Single crowns, inlays, onlays, and veneers, artificial teeth for dental prostheses	A1, A2, A3, B1, BL	DLP	Saremco Dental AG, Rebstein, Switzerland
Formlabs Permanent Crown Resin	Silanized dental glass, methyl benzoylformate, diphenyl(2,4,6-trimethylbenzoyl) phosphine oxide, 4.4'-isopropylidiphenol, ethoxylated and 2-methylprop-2enoic acid, inorganic fillers	116 MPa	Single crowns, inlays, onlays, and veneers	A2, A3, B1, C2	SLA	Formlabs GmbH, Berlin, Germany
Flexcera Smile Ultra+	Acrylates, methylacrylates, methacrylated oligomers and monomers, photo initiators, colorants/dyes, fillers and absorbers	Unspecified	Single crowns, inlays, onlays, and veneers, artificial teeth for dental prostheses	A1, A2, A3, A3.5, B1, BL	DLP	EnvisionTEC GmbH, Gladbeck, Germany
Irix® Plus	Acrylate monomers, Inorganic fillers, photoinitiator, stabilizers	>100 MPa	Single crowns, up to 3-unit bridges, inlays, onlays, and veneers	A1, A2, A3, A3.5, B1, N, multicoloured	SLA	DWS, Thiene (VI), Italy
Irix® Max	Acrylate monomers, Inorganic fillers, photoinitiator, stabilizers	>80 MPa	Single crowns, up to 3-unit bridges, inlays, onlays, and veneers	A1, A2, A3, A3.5, B1, N, multicoloured	SLA	DWS, Thiene (VI), Italy

Data was collected from the manufactures' websites and brochures. 3D: Three-dimensional, DLP: Digital light processing, SLA: Stereolithography.

to overcome the challenges of mimicking complex and 3D functional biological tissues.[36,47] Technological advances show that 3D bio-printing shows great promise for future generations in the fabrication of whole teeth and other oral tissues.[36] Microscale technologies have great potential for *in vitro* and *in vivo* improvements of tooth-like structures, as they can produce microstructures, provide open canals, promote vascularization, improve diffusion, help regulate cell activity and facilitate efficient approaches.[48] The "*microscale technology approach*" developed for the control of activities at the cellular level can be realized by soft lithography or photolithography.[36,49]

Soft lithography is a technique where patterned silicon materials such as poly (dimethylsiloxane) are used as master casting templates for molding elastomeric materials.[49] Photolithography is an another technique used to create micro-scale features in scaffolds.

There is increasing consensus that 3D micro-channels created by these techniques can help promote cell metabolism and play an important role in achieving a reliable technique for tooth regeneration.[36,50] Even after achieving the advanced technology for the regeneration of dental structures, the major challenges of the application of these technologies in dental clinical practice are their high cost, difficulties in public accessibility, and the ethical debates about which source of cell (patient or donor) and type of cell (adult or fetal) should be chosen for regeneration.[36]

Study Limitations

Although there are case reports and *in vivo* studies on the clinical use of these technologies for surgical, orthodontic, endodontic, and prosthodontic applications in the literature, there are few studies on their restorative applications, owing to the limitations of the materials used with additive manufacturing technologies.

Conclusion

Additive manufacturing technologies, which have become widespread in many fields due to their success in manufacturing complex structures, have started to attract interest in regenerative and restorative dental applications as an alternative to conventional and subtractive methods. This technology, which is employed in many areas of dentistry, has raised hopes for the total regeneration of dental tissues, particularly with the ability to create dynamic models with 4DP.

MAIN POINTS

- Additive manufacturing technologies avoid a great deal of material waste compared to subtractive manufacturing technologies.
- Integration of additive manufacturing technologies into the field of dentistry is becoming more widespread day by day with the continuous development of 3D printers and their compatible resins.
- In restorative dentistry, additive manufacturing technologies are utilized in digital wax-up and guide preparations, the fabrication of indirect temporary/permanent dental restorations, as well as regenerative and tissue engineering applications.

ETHICS

Authorship Contributions

Surgical and Medical Practices: T.Ö., Concept: T.Ö., İ.K., Design: T.Ö., İ.K., Data Collection and/or Processing: T.Ö., Analysis and/or Interpretation: T.Ö., Literature Search: T.Ö., Writing: T.Ö.

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REFERENCES

1. Miyazaki T, Hotta Y, Kunii J, Kuriyama S, Tamaki Y. A review of dental CAD/CAM: current status and future perspectives from 20 years of experience. Dent Mater J. 2009; 28(1): 44-56.
2. Şahin E, Aktaş GÜ, Özcan N, Hasanoğlu Aydın D, Akça KI. Restoratif diş hekimliğinde CAD/CAM klinik uygulamalar: Sirona CEREC sistemi. Clinical Dentistry and Research. 2009; 33(4): 34-40.
3. Şeker E, Ersoy AE. Diş hekimliğinde restoratif CAD/CAM sistemleri. ADO Klinik Bilimler Dergisi. 2010; 4(1): 493-504.
4. Koch GK, Gallucci GO, Lee SJ. Accuracy in the digital workflow: from data acquisition to the digitally milled cast. J Prosthet Dent. 2016; 115(6): 749-54.
5. Liu Y, Di P, Zhao Y, Hao Q, Tian J, Cui H. Accuracy of multi-implant impressions using 3D-printing custom trays and splinting versus conventional techniques for complete arches. Int J Oral Maxillofac Implants. 2019; 34(4): 1007-14.
6. Merklein M, Junker D, Schaub A, Neubauer F. Hybrid additive manufacturing technologies—an analysis regarding potentials and applications. Phys Procedia. 2016; 83: 549-59.
7. Rekow ED. Digital dentistry: The new state of the art - Is it disruptive or destructive? Dent Mater. 2020; 36(1): 9-24.
8. Lebon N, Tapie L, Duret F, Attal JP. Understanding dental CAD/CAM for restorations - dental milling machines from a mechanical engineering viewpoint. Part A: chairside milling machines. Int J Comput Dent. 2016; 19(1): 45-62.
9. Ting-Shu S, Jian S. Intraoral digital ımpression technique: a review. J Prosthodont. 2015; 24(4): 313-21.
10. Correia AR, Sampaio Fernandes JC, Cardoso JA, Leal-Da-Silva C. CAD-CAM: informatics applied to fixed prosthodontics. Rev Odontol UNESP. 2006; 35(2): 183-9.
11. Liu Q, Leu MC, Schmitt SM. Rapid prototyping in dentistry: technology and application. Int J Adv Manuf Technol. 2006; 29: 317-35.
12. van Noort R. The future of dental devices is digital. Dent Mater. 2012; 28(1): 3-12.
13. Alghazzawi TF. Advancements in CAD/CAM technology: options for practical implementation. J Prosthodont Res. 2016; 60(2): 72-84.
14. Braian M, Jönsson D, Kevci M, Wennerberg A. Geometrical accuracy of metallic objects produced with additive or subtractive manufacturing: A comparative in vitro study. Dent Mater. 2018; 34(7): 978-93.
15. Kim HR, Jang SH, Kim YK, Son JS, Min BK, Kim KH, et al. Microstructures and mechanical properties of Co-Cr dental alloys fabricated by three CAD/CAM-based processing techniques. Materials (Basel). 2016; 9(7): 596.

16. Kocaağaoğlu H, Kılınç Hİ, Albayrak H, Kara M. In vitro evaluation of marginal, axial, and occlusal discrepancies in metal ceramic restorations produced with new technologies. J Prosthet Dent. 2016; 116(3): 368-74.

17. González-Henríquez CM, Sarabia-Vallejos MA, Rodriguez-Hernandez J. Polymers for additive manufacturing and 4D-printing: Materials, methodologies, and biomedical applications. Progress in Polymer Science. 2019; 94: 57-116.

18. Mani M, Lyons KW, Gupta SK. Sustainability characterization for additive manufacturing. J Res Natl Inst Stand Technol. 2014; 119: 419-28.

19. Revilla-León M, Özcan M. Additive manufacturing technologies used for 3D metal printing in dentistry. Current Oral Health Reports. 2017; 4(3): 1-8.

20. Anadioti E, Kane B, Soulas E. Current and emerging applications of 3D printing in restorative dentistry. Current Oral Health Reports. 2018; 5(10): 133-9.

21. Ligon SC, Liska R, Stampfl J, Gurr M, Mülhaupt R. Polymers for 3D printing and customized additive manufacturing. Chem Rev. 2017; 117(15): 10212-90.

22. Revilla-León M, Meyers MJ, Zandinejad A, Özcan M. A review on chemical composition, mechanical properties, and manufacturing work flow of additively manufactured current polymers for interim dental restorations. J Esthet Restor Dent. 2019; 31(1): 51-7.

23. Alharbi N, Osman R, Wismeijer D. Effects of build direction on the mechanical properties of 3D-printed complete coverage interim dental restorations. J Prosthet Dent. 2016; 115(6): 760-7.

24. Reinhardt C, Passinger S, Chichkov BN, Marquart C, Radko IP, Bozhevolnyi SI. Laser-fabricated dielectric optical components for surface plasmon polaritons. Opt Lett. 2006; 31(9): 1307-9.

25. Tamay DG, Dursun Usal T, Alagoz AS, Yucel D, Hasirci N, Hasirci V. 3D and 4D printing of polymers for tissue engineering applications. Front Bioeng Biotechnol. 2019; 7: 164.

26. Singh A, Katiyar M, Garg A. Understanding the formation of PEDOT: PSS films by ink-jet printing for organic solar cell applications. RSC advances. 2015; 5(96): 78677-85.

27. Groth C, Kravitz ND, Jones PE, Graham JW, Redmond WR. Three-dimensional printing technology. J Clin Orthod. 2014; 48(8): 475-85.

28. Singh R, Gupta A, Tripathi O, Srivastava S, Singh B, Awasthi A, et al. Powder bed fusion process in additive manufacturing: an overview. Materials Today: Proceedings. 2020; 26: 3058-70.

29. Önoral Ö. New approaches in computer aided printing technologies. Cumhuriyet Dental Journal. 2017; 19(3): 256-66.

30. Koutsoukis T, Zinelis S, Eliades G, Al-Wazzan K, Rifaiy MA, Al Jabbari YS. Selective laser melting technique of Co-Cr Dental alloys: a review of structure and properties and comparative analysis with other available techniques. J Prosthodont. 2015; 24(4): 303-12.

31. Gokuldoss PK, Kolla S, Eckert J. Additive Manufacturing Processes: Selective Laser Melting, Electron Beam Melting and Binder Jetting-Selection Guidelines. Materials (Basel). 2017; 10(6): 672.

32. Ashammakhi N, Ahadian S, Zengjie F, Suthiwanich K, Lorestani F, Orive G, et al. Advances and future perspectives in 4D bioprinting. Biotechnol J. 2018; 13(12): e1800148.

33. Zhu Z, Dhokia V, Newman ST, Nassehi A. Application of a hybrid process for high precision manufacture of difficult to machine prismatic parts. The International Journal of Advanced Manufacturing Technology. 2014; 74: 1115-32.

34. Xia J, Li Y, Cai D, Shi X, Zhao S, Jiang Q, et al. Direct resin composite restoration of maxillary central incisors using a 3D-printed template: two clinical cases. BMC Oral Health. 2018; 18(1): 158.

35. Krey KF, Ratzmann A, Metelmann PH, Hartmann M, Ruge S, Kordaß B. Fully digital workflow for presurgical orthodontic plate in cleft lip and palate patients. Int J Comput Dent. 2018; 21(3): 251-9.

36. Amrollahi P, Shah B, Seifi A, Tayebi L. Recent advancements in regenerative dentistry: A review. Mater Sci Eng C Mater Biol Appl. 2016; 69: 1383-90.

37. Roseti L, Parisi V, Petretta M, Cavallo C, Desando G, Bartolotti I, et al. Scaffolds for Bone Tissue Engineering: State of the art and new perspectives. Mater Sci Eng C Mater Biol Appl. 2017; 78: 1246-62.

38. Segundo ÂR, Saraiva S, de Castro C, Sesma N, Bohner L, Andretti FL, et al. CAD-CAM natural restorations-Reproducing nature using a digital workflow. J Esthet Restor Dent. 2023; 35(7): 993-1000.

39. Silva BPD, Stanley K, Gardee J. Laminate veneers: Preplanning and treatment using digital guided tooth preparation. J Esthet Restor Dent. 2020; 32(2): 150-60.

40. Coachman C, Gurel G, Calamita M, Morimoto S, Paolucci B, Sesma N. The influence of tooth color on preparation design for laminate veneers from a minimally invasive perspective: case report. Int J Periodontics Restorative Dent. 2014; 34(4): 453-9.

41. Shamseddine L, Mortada R, Rifai K, Chidiac JJ. Marginal and internal fit of pressed ceramic crowns made from conventional and computer-aided design and computer-aided manufacturing wax patterns: An in vitro comparison. J Prosthet Dent. 2016; 116(2): 242-8.

42. Mai HN, Lee KB, Lee DH. Fit of interim crowns fabricated using photopolymer-jetting 3D printing. J Prosthet Dent. 2017; 118(2): 208-15.

43. Oh JH, An X, Jeong SM, Choi BH. A digital technique for fabricating an interim implant-supported fixed prosthesis immediately after implant placement in patients with complete edentulism. J Prosthet Dent. 2019; 121(1): 26-31.

44. Tahayeri A, Morgan M, Fugolin AP, Bompolaki D, Athirasala A, Pfeifer CS, et al. 3D printed versus conventionally cured provisional crown and bridge dental materials. Dent Mater. 2018; 34(2): 192-200.

45. Graf T, Erdelt KJ, Güth JF, Edelhoff D, Schubert O, Schweiger J. Influence of pre-treatment and artificial aging on the retention of 3D-printed permanent composite crowns. Biomedicines. 2022; 10(9): 2186.

46. Atria PJ, Bordin D, Marti F, Nayak VV, Conejo J, Benalcázar Jalkh E, et al. 3D-printed resins for provisional dental restorations: Comparison of mechanical and biological properties. J Esthet Restor Dent. 2022; 34(5): 804-15.

47. Chang J, He J, Mao M, Zhou W, Lei Q, Li X, et al. Advanced material strategies for next-generation additive manufacturing. Materials (Basel). 2018; 11(1): 166.

48. Khademhosseini A, Langer R, Borenstein J, Vacanti JP. Microscale technologies for tissue engineering and biology. Proc Natl Acad Sci U S A. 2006; 103(8): 2480-7.

49. Hacking SA, Khademhosseini A. Applications of microscale technologies for regenerative dentistry. J Dent Res. 2009; 88(5):409-21.

50. Ling Y, Rubin J, Deng Y, Huang C, Demirci U, Karp JM, et al. A cell-laden microfluidic hydrogel. Lab on a Chip. 2007; 7(6): 756-62.