REVIEW
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The Use of Additive Manufacturing Technologies in Restorative Dentistry

Özberk and Karakaya. Additive Manufacturing in Restorative Dentistry

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Abstract
In today's era, as in many other industries, there is a rapid trend towards digitalization in the dentistry and the use of computer-aided design and computer-aided manufacturing (CAD/CAM) technologies is 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 as 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 in various dental applications, will become the main method for digital manufacturing in dentistry at future. In this review; it is aimed to examine the computer-aided manufacturing methods that are commonly used in the dentistry; to evaluate the advantages and disadvantages of these methods systematically; to examine the functioning processes of additive manufacturing technologies that are used in dentistry; and to evaluate the use and development of these additive manufacturing techniques in the 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 the medical database (MEDLINE- PubMed, EMBASE).

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INTRODUCTION

Computer-aided design and computer-aided manufacturing (CAD/CAM) applications have proliferated in dentistry as a result of rising technological advancements in the field (Figure 1, 2). These applications are popular due to benefits like 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 methodology to complete indirect restorations made of a material with superior biological and mechanical qualities in a single session and 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.[3,4,5] Due to its ability to generate more complex, sophisticated structures and reduced material waste, additive manufacturing is now being employed as a substitute for subtractive methods in dentistry.[6,7]
The aim of this article is to give information about three dimensional (3D) printing technologies that 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 that 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 (Computer Aided Design). The final element, CAM (Computer Aided Manufacturing), makes it possible to produce the restoration that 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 collecting, 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 squandered 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] 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 (ASTM) 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, the additive manufacturing technology is 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 base 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 material and support material, 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 additive manufacturing processes build and combine layers in a variety of ways, each methodology essentially comprises of 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 that uses light-activated polymerization to selectively polymerize a liquid photopolymer in a vat. Vat polymerization is a process used in additive manufacturing technologies like stereolithography, digital light processing, continuous liquid interface production, and multiphoton polymerization.[22]

Stereolithography (SLA): Stereolithography 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): Digital light processing is based on the principle of layer-by-layer production by 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 to be produced. In addition, this technology uses a production direction opposite to SLA.[21]

Continuous liquid interface production (CLIP): The working principle is almost 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 (MPP): 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 technological lasers, this technique has become feasible. However, the production time and the size of the object that can be produced are still not at the desired level (production size limit 30x30µm).[24] In contrast to traditional stereolithography, multiphoton polymerization is the process of producing the entire desired object in one time by multiphoton polymerization without using the layer-on-layer technique. Thus, complex structures that 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 (FDM): The most commonly used printer technology for model manufacturing. In this technique, the production is in the form of forming layers with melted thermoplastic filaments.[25] Wax, metals and ceramics are the main materials used in this technique.

Inkjet Printers (IJP)

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

Thermal Inkjet Printing: The term thermal inkjet printer; It is 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 depending on the pressure of air bubbles which formed by 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 formed layer is polymerized with a UV light source.[27]

Aerosol Jet Printers (AJ-P)

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 (3DP)

3D printers 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 (PBF)

This method melts and fuses the powder particles on the production platform using thermal energy produced by a laser or electron source.[28] There are now three different 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 like melting temperature, energy source, energy power, thermal conductivity, room conditions, temperature to be reached, layer thickness, structure orientation, and particles.[19]

Selective Laser Sintering (SLS): This technique uses laser energy from carbon dioxide (CO_2) and neodymium-doped ytrium alumunium garnet (Nd-YAG) lasers to fuse plastic, ceramic or glass particles.

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

Rapid Freeze Prototyping (RFP)

RFP produces dental restorations using ice molds instead of traditional wax molds. The technique is a new and environmentally friendly solid freeforming process that 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 (LENS)

LENS is also called Laser Metal Deposition (LMD) and Laser Coating (LC). The powder is completely melted by a powerful laser beam, similar to the SLM technique, but in this technique the powder particles to be melted are sprayed by a nozzle.

4D Printers (4DP)

Unlike 3D printers, which manufacture static materials that maintain the same shape and properties throughout their life and lifetime, 4D printers 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 that can calculate the shape and dimensional changes that 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 that 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 (LOM) is classified within additive manufacturing systems; it is actually a system that works with a hybrid approach, but since the additive manufacturing part is highly dominant, it is usually mentioned under 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 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 such as high aesthetic expectations of patients in the anterior region, deficiencies in patient-doctor communication, patient concerns about the appearance to be obtained at the end of the procedure; mock-up, wax-up and guide applications may be preferred in order to create appropriate form, size, contact relationships and to ensure that the patient and dentist are on the same side 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.[39] (Figure 3).

This development provides very fast feedback on any changes in the design plan instead of traditional intraoral mock-up or wax-up methods used on the model in aesthetic services such as smile design.[40] In addition to the wax-up 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 consulted with the patient, and if desired, silicone mock-ups can be prepared on this model.[38] (Figure 4).
Recently, this technology has enabled the development of 3D printed rigid preparation guides with a new design that makes it possible to overcome some of the limitations of silicone indexes and improves the ability to visualise the teeth. Furthermore, in the multidisciplinary treatment protocol of aesthetic anterior restorations, it has been possible to 3D print crown lengthening guides that can be used in the periodontal surgery step to improve facial aesthetics by restoring the harmony between hard and soft tissues.[38,39] On the other hand, after the periodontal and surgical procedures 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 the temporary crown are higher than those fabricated with the conventional direct technique because of 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 because they limitate the shape that 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 3D printers.[44] However, additional research is needed on the biocompatibility and long-term outcomes of the polymers used in additive manufacturing.[22] (Figure 5).

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 materials used in conventional and subtractive methods.[46] The 3D printed hybrid composite resins of different brands available in the market for use in permanent restorations are shown in (Table 1).

Regenerative Applications and Tissue Engineering

Because 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, 3D bioprinting of dental and craniofacial tissues has been proposed to overcome the challenges of mimicking complex and 3D functional biological tissues.[36,47] Technological advances show that 3D bioprinting 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 improvement 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)/(PDMS) 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 are increasing consensus that 3D microchannels 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 an advanced technology for the regeneration of dental structures; the major challenges of the application of these technologies in dental clinical practice are the high cost, difficulties in public accessibility, and the ethical debates about the which source of cell (patient or donor) and type of cell (adult or fetal) choose for regeneration.[36]

CONCLUSION

Additive manufacturing technologies, which have become widespread in many fields with 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 total regeneration of dental tissues, particularly with the ability to create dynamic models with 4D printers. 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 restorative applications, owing to the limitations of the materials used with additive manufacturing technologies.

MAIN POINTS

-Additive manufacturing technologies avoid 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 preparation, fabrication of indirect temporary/permanent dental restorations, regenerative and tissue engineering applications.

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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 have been collected from the manufactures' websites and their material brochures.						

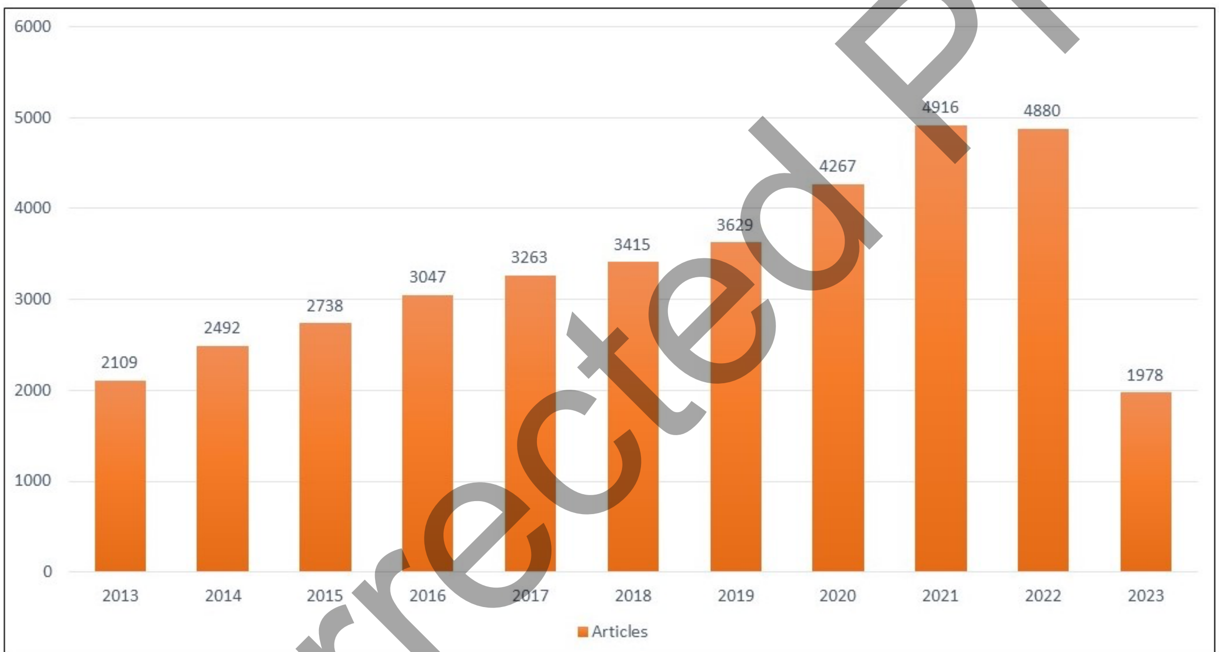

Figure 1. Year-wise (2013-2023) literature production on dentistry field in additive manufacturing technology.

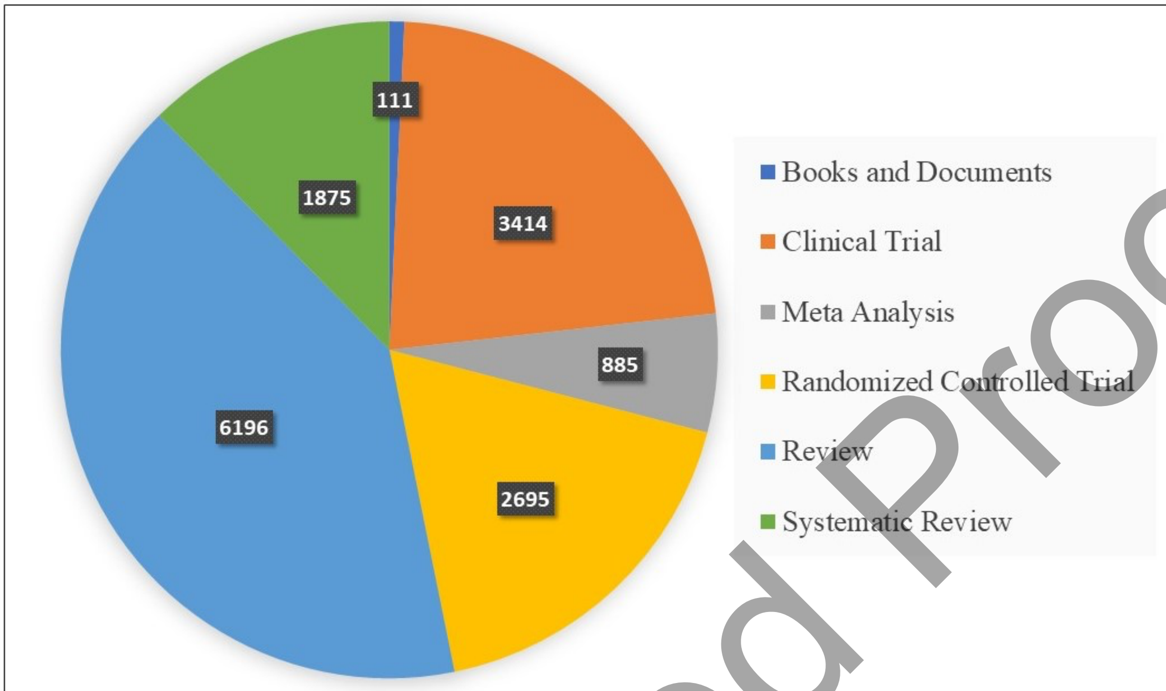

Figure 2. The ratio of the types of articles published on additive manufacturing technology in the field of dentistry.

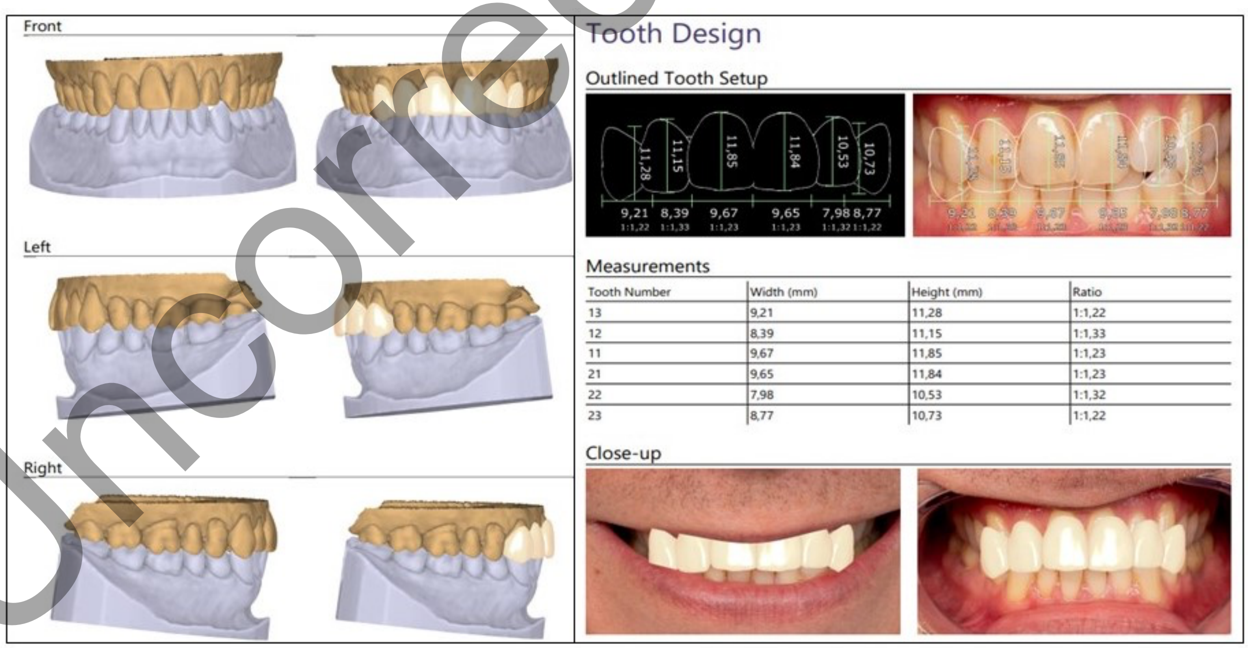

Figure 3. Digital wax-up design in the anterior region in CAM design software.

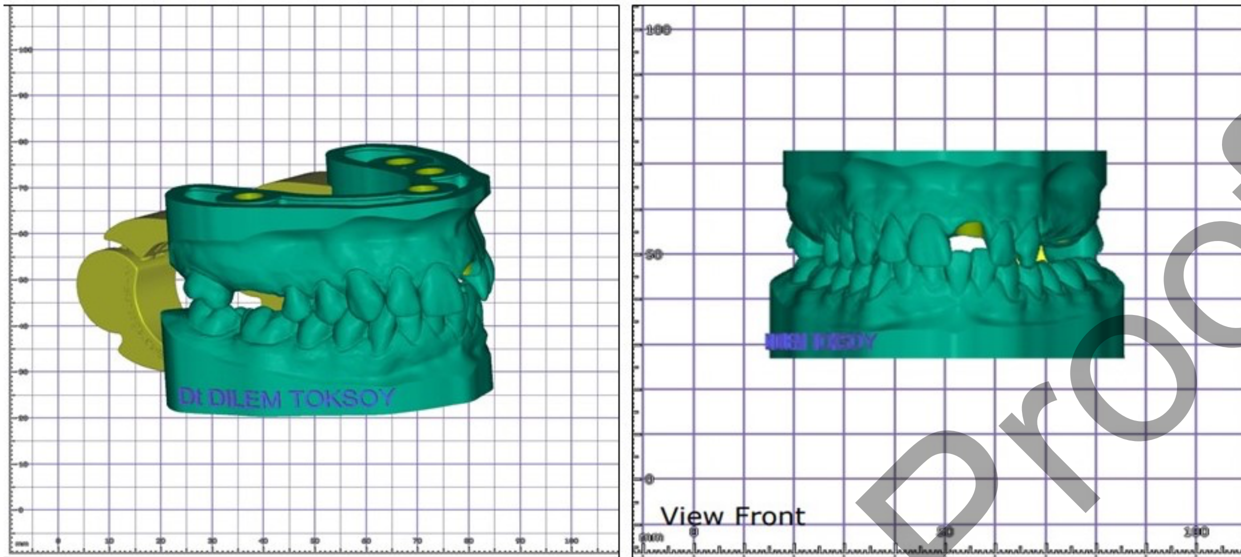

Figure 4. 3D printed model design.

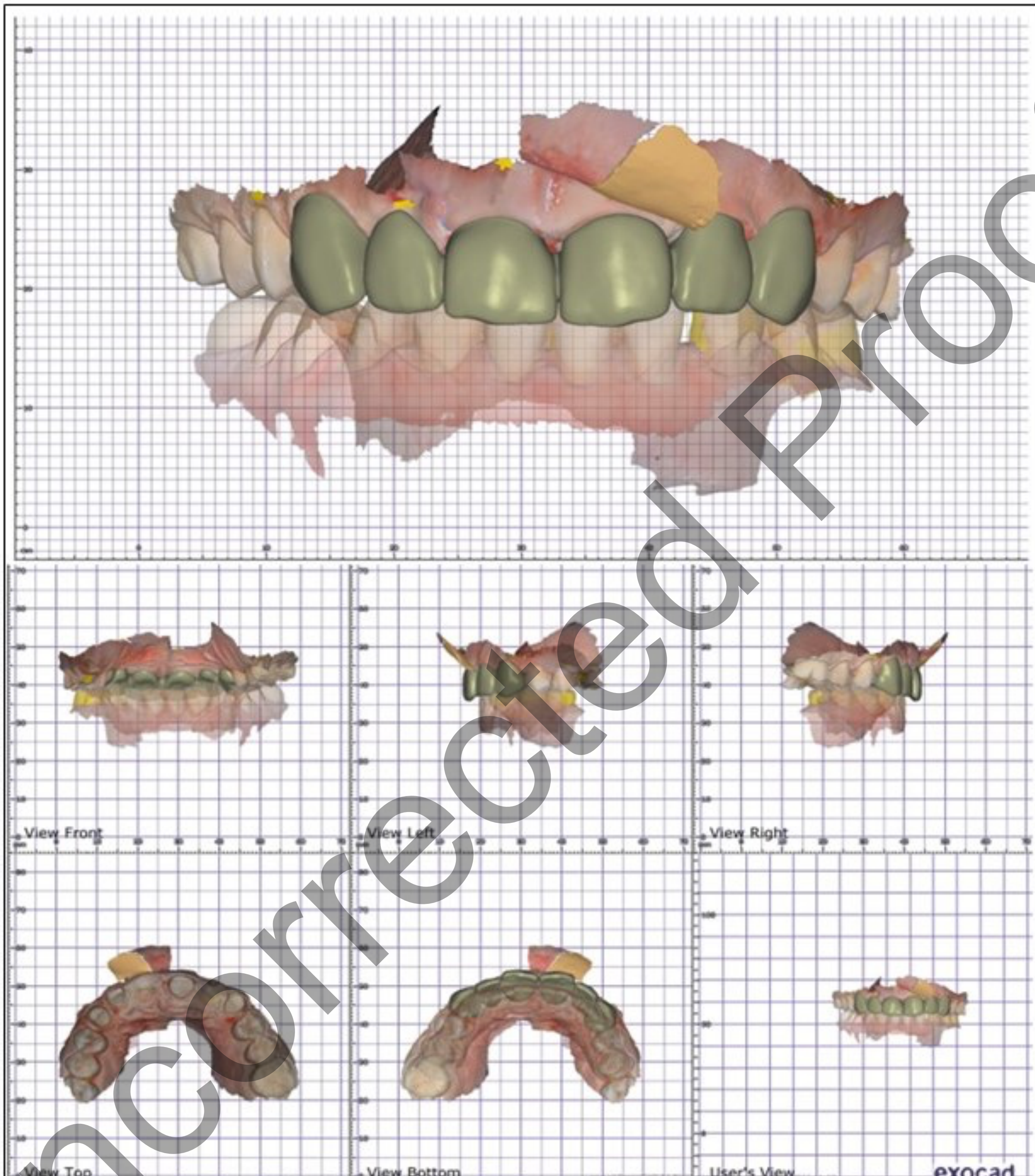

Figure 5. Anterior temporary restoration designed for manufacturing on a 3D printer.

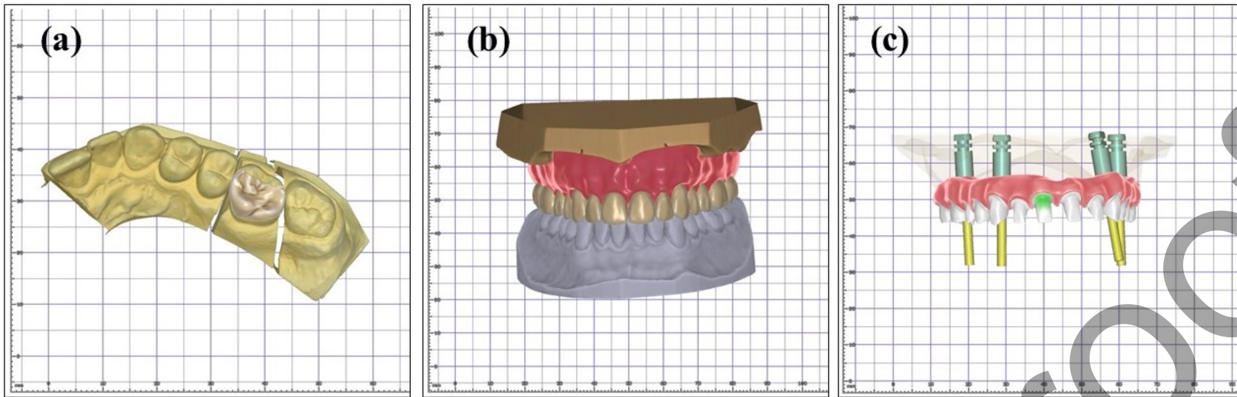

Figure 6. Onlay restoration designed for fabrication with 3D printable hybrid composite resins (a), total prosthesis designed for fabrication with 3D printable hybrid composite resins (b), implant supported prosthesis designed for fabrication with 3D printable hybrid composite resins (c).