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Review

Properties of CAD/CAM 3D Printing Dental Materials and Their Clinical Applications in Orthodontics: Where Are We Now?

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Abstract: In the last years, both medicine and dentistry have come across a revolution represented by the introduction of more and more digital technologies for both diagnostic and therapeutic purposes. Additive manufacturing is a relatively new technology consisting of a computer-aided design and computer-aided manufacturing (CAD/CAM) workflow, which allows the substitution of many materials with digital data. This process requires three fundamental steps represented by the digitalization of an item through a scanner, the editing of the data acquired using a software, and the manufacturing technology to transform the digital data into a final product, respectively. This narrative review aims to discuss the recent introduction in dentistry of the abovementioned digital workflow. The main advantages and disadvantages of the process will be discussed, along with a brief description of the possible applications on orthodontics.

Keywords: 3D printing; CAD/CAM; additive manufacturing; orthodontics; orthodontic appliances; manufacturing; digital workflow; analogic workflow; mechanical properties

1. Introduction

In recent years, the introduction of digital technologies in dentistry has represented a significant breakthrough. In particular, intra-oral scanning is becoming a more and more developed technique with a progressive substitution of the traditional dental impressions [1]. These systems showed good precision [2] and excellent patient feedback [3]. Despite digital dental models allowing the diagnosis, treatment planning and simulation of the results at the end of the therapy, they cannot directly reproduce physical models and appliances. To do so, this 3D workflow needs a computer-aided design and manufacturing (CAD-CAM) process, which consists of the elaboration of the digital data, previously acquired with the intra-oral scanner, and the production of a precise 3D physical model [4]. The rise of additive manufacturing, also known as 3D printing, dates to the 1980s, despite its introduction in dentistry being much more recent, because of the initial high cost, as well as its low speed and accuracy. In the meanwhile, an increasing number of printable biomaterials have been developed, thus significantly contributing to almost every field of dentistry [5,6]. To date, several studies have been conducted to evaluate the mechanical properties of 3D-printed materials, such as microhardness, but no extensive literature specifically exists for dental materials [7,8].

In orthodontics, as in other fields of dentistry, five different printing technologies are now available, that is, fused deposition modeling/fused filament fabrication (FDM/FFF), stereolithography (SLA), digital light processing (DLP), selective laser sintering/melting (SLS/SLM) and electron beam melting (EBM), Binder Jetting (BJ) and Material Jetting (MJ) [1,9–15].

As previously said, 3D printing almost covers every specialty of dentistry, including orthodontics [16–21]. A bibliometric analysis using Scopus and PubMed Databases has been conducted using the following MeSH terms: TITLE-ABS-KEY (printing AND three-dimensional AND dentistry) and (printing AND three-dimensional AND orthodontics). The bibliometric research was conducted in January 2021, so data for this year are ongoing. In the last two decades, an increase in the publication of indexed literature about dental 3D printing applications has been noted for both keywords (Figure 1).

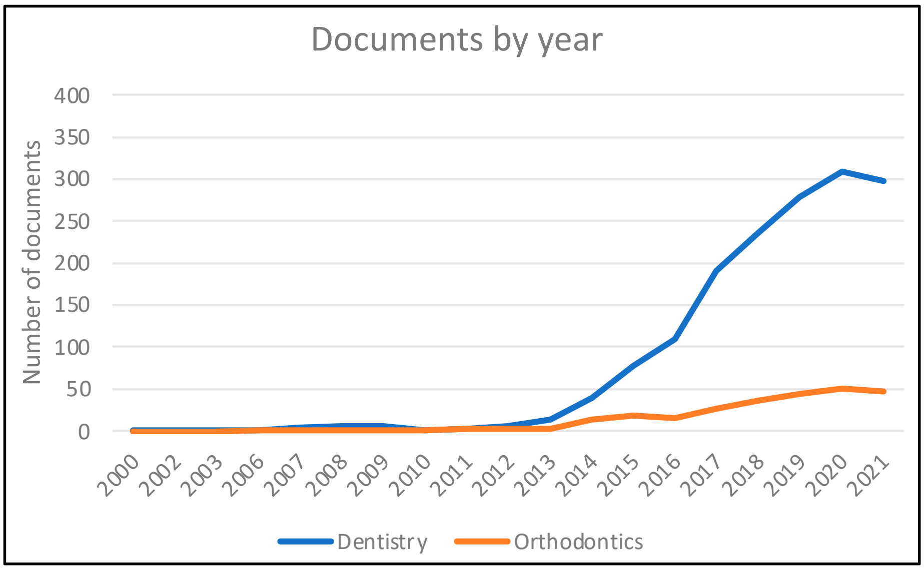

Figure 1. Bibliometric analysis with Scopus and PubMed Database considering years from 2003 to 2021 (data for the latter year are ongoing).

As regards orthodontics, articles account for 90.87% of the total documents, while reviews constitute 9.13% of the total. As there is a scarcity of clinical trials of 3D-printed appliances, many narrative reviews have been published until now. Articles, instead, are mainly case reports and in vitro/laboratory studies. Scopus and PubMed search engines have been used to perform the present narrative review. All relevant articles are supposed to have been included.

Focusing on the latter, the applicability of the digital workflow regards both dental casts and direct appliances. The present article aims to perform a narrative description of the digital workflow, especially focusing on orthodontics and the applications of the process in this field.

2. Three Dimensional Printing Technologies

The general term "3D Printing" or "Additive Manufacturing" encompasses different technologies, which differ in the way each layer is deposited and processed and in the type of material used. The first classification of 3D printing technologies was proposed in 2009 by the "ASTM Committee F42 on Additive Manufacturing Technologies" established the same year. Beside the classification, the Committee also proposed the term Additive

Manufacturing instead of Rapid Prototyping, at that time considered a synonym of 3D printing, thus suggesting a more inclusive application of 3D printing technologies [22]. As it concerns orthodontics, according to the literature the most common technologies are stereolithography (SLA), digital light processing (DLP), fused deposition modeling (FDM)/fused filament fabrication (FFF), selective laser sintering (SLS)/melting (SLM) and electron beam melting (EBM), Binder Jetting (BJ) and Material Jetting (MJ). The main characteristics of each technology are described below.

2.1. Stereolithography (SLA) and Digital Light Processing (DLP)

Stereolithography (SLA) is based on the use of a photocurable liquid resin as a printing material (photopolymer) [23]. Its working process consists of a layer-by-layer model printing starting from liquid resins exposed either to the photopolymerizing action of an ultraviolet laser source (SLA) or a visible light projector (DLP). The former modality requires a progressive movement of the laser across the layer, whereas the former guarantees the curing of an entire resin layer thus resulting in a faster process. In this way, the cross-linking of the polymer and its hardening are promoted by the laser beam, that belongs to the ultraviolet wavelength. A necessary step following SLA/DLP printing is represented by the post-processing of the printed model to avoid its shrinkage and distortions. Accordingly, an alcohol solution removes all the uncured resin, subsequently heat and ultraviolet light are required to harden the model, generally put inside an illumination chamber [6,14,17].

Digital light processing (DLP) is a 3D printing technology that is quite similar to SLA, since a photopolymer is used as a printing material [23]. In particular, the latter is cured with a digital micromirror device (DMD). Different from SLA, the curing light is projected on the entire layer, while the former technique is based on a spot laser beam. This difference results in a faster procedure for DLP [24].

2.2. Fused Deposition Modeling/Fused Filament Fabrication (FDM/FFF)

Fused deposition modeling (equivalent to the not trademarked term "fused filament fabrication"—FFF) consists of the formation of solid objects using a thermoplastic material [23]. This one is heated until reaching a melting temperature and then released through extrusion heads by the printer in a specific pattern, thus forming a single layer of an object [17]. Therefore, the material is released layer-by-layer and these strata are fused together when the entire structure solidifies. Beside supports removal, no further procedures are usually required on the material itself to improve mechanical properties [18].

2.3. Selective Laser Sintering (SLS)/Melting (SLM) and Electron Beam Melting (EBM)

Selective laser sintering/melting (SLS/SLM) aims to print 3D objects using powder materials (e.g., polyamides, polycaprolactone, hydroxyapatite, stainless steel, titanium, and Co/Cr) [23]. This powder is heated above the glass transition or melting temperature using a high energy CO_2 beam, thus sintering/melting the particles together in a specific pattern. The curing of the powder proceeds according to a layer-by-layer step, until the entire material is printed. The post-printing processing consists of the removal of the excess powder particles for plastic materials [6], while it is far more challenging for metals, for which specific post-processing is required to remove support structures (sawing, CNC machining etc.).

Electron beam melting (EBM) technology is based on the use of metal powder (stainless steel, titanium, etc.) as a printing material as well. In this case, the powder is submitted to sintering by a computer-controlled electron beam in a vacuum (differently from SLS which uses a laser beam) [17].

2.4. Binder Jetting (BJ)

Binder Jetting (BJ) is a technique aimed at realizing objects by adding a pattern of binding liquid on a powder substrate [23]. The structure results from the reaction between the liquid and the powder, then the phase transformation is promoted by ultraviolet curing, chemical or thermal reaction, or dehydration [17,25].

2.5. Material Jetting (MJ)

An evolution of SLA technology is represented by Material Jetting (MJ), which employs a liquid photopolymer as a printing material. This latter is extruded by a series of small nozzles on a building platform and then cured with UV light. Supportive structures are realized with layers of photopolymeric material as well. Then, supporting materials can be easily removed at the end of the printing process. Different from SLA, objects printed with Material Jetting printers are cured at their maximum rate, thus not requiring an additional post-curing procedure [23].

2.6. Main Features

SLM technologies are commonly the most expensive due to the high cost of the base material (fine metal powder) and to the presence of one or more high power laser sources in the machine. MJ technology is also commonly expensive, especially in terms of the material's cost. FFF machines are the cheapest both in terms of machine and material cost. They are also capable of processing the widest range of materials (thermoplastic polymers). On the other hand, FFF machines feature the lowest printing quality. BJ, MJ and some SLM machines working with polymers can feature full color resolution, offering great advantages in terms of anatomical modeling. BJ, SLS and some SLM working with polymers can avoid the use of support structures to be removed after the printing, thanks to their functioning principles structure [15].

The application of the aforementioned technologies varies according to their technical features (e.g., minimum detail resolution, accuracy, speed of production) and to the materials' specifications (e.g., level of biocompatibility, mechanical properties) [16]. Table 1 shows the most relevant 3D-printable materials, their applications in dentistry and the major features related to their use [15,16,26–34].

Table 1. Groups of materials printable with the different 3D-printing technologies, their applications in dentistry, and major features.

Materials	Applications in Dentistry	General Features
Bio-compatible photopolymer resins	Splint, tray, temporary restoration, gingiva mask	Rigid and deformable polymers certified for contact with skin and mucous tissue for a prescribed time. Materials and machines devoted to the dental field are available in this category (e.g., 3D printed crown and bridge materials → flexural strength: 100–140 MPa; flexural modulus: 0.5–2 GPa; Vickers hardness: 4–20 MPa). Available in SLA and MJ technologies. Photopolymer resins used for 3D printing must be acknowledged by Food and Drug Administration (FDA); their monomeric form is typically quite toxic even though the properly polymerized resin is not.
Photopolymer resins	Model, castable surgical guide	Rigid and deformable polymers to be used in SLA or MJ technologies. Wide range of mechanical properties are available, but usually it is not possible to reach high mechanical performance (beside the use of material filled with ceramic or metal powder to be sintered after the printing). E.g., 3D-printed acrylic resin → flexural strength: 63.93–113.16 MPa; Vickers hardness: 25.16–34.62 VHN; surface roughness: 0.12–5.77 µm.
Co-Cr Titanium	Crowns, implants, partial dentures, hyrax, lingual arch, transpalatal arch, retainers	High density (Co-Cr: 10 g/cm^3; Titanium: 4.5 g/cm^3), hardness (Vickers hardness Co-Cr: 550–800 MPa; Vickers hardness Titanium: 830–3420 MPa) and elastic modulus higher than bone structures (Co-Cr: 220 GPa; Titanium: 110 GPa; Cortical bone: 18–20 GPa; Trabecular bone: 10–14 GPa). Biocompatible and implantable materials available in SLM/EBM machines.

Table 1. *Cont.*

Materials	Applications in Dentistry	General Features
Thermoplastic materials for FDM/FFF printers	Model	Polylactides (PLA) (density: 1.3 g/cm^3; elastic modulus: 2.7–16 GPa)
		Acrylonitrile-butadiene-styrene (ABS) (density: 1.07 g/cm^3; elastic modulus: 1.79–3.2 GPa)
		Acrylonitrile Styrene Acrylate (ASA) (density: 1.08 g/cm^3; elastic modulus: 2.6 GPa) are rigid materials commonly available in almost all the FDM/FFF machines.
		Thermoplastic Polyurethane (TPU) (density: 1.23 g/cm^3; elastic modulus: 0.621–5.50 GPa) is a deformable material with a high elongation at break (it can be used to simulate soft tissue, although available only with high Shore A values—above 50)
Techno-polymers for FDM/FFF or SLS printers	Implant fixtures	PEEK features an excellent chemical resistance, biocompatibility and good mechanical properties with a slightly lower Young Modulus with respect to bony structures (PPEK: 3.6 GPa; Cortical bone: 18–20 GPa; Trabecular bone: 10–14 GPa).

3. The Digital Workflow

The steps of the "partial" digital workflow can be divided into the following five sequential steps: acquisition of the intra-oral scan, elaboration of the digital model, 3D printing, post-printing processing, and, finally, production of the model [1].

3.1. Intra-Oral Scanning

The purpose of this step is the acquisition of the morphology of the teeth and the adjacent soft tissues using an intraoral scanner (Figure 2). The image acquired must be exported as a standard tessellation language (STL) file in order to be available for the subsequent digital elaboration [1].

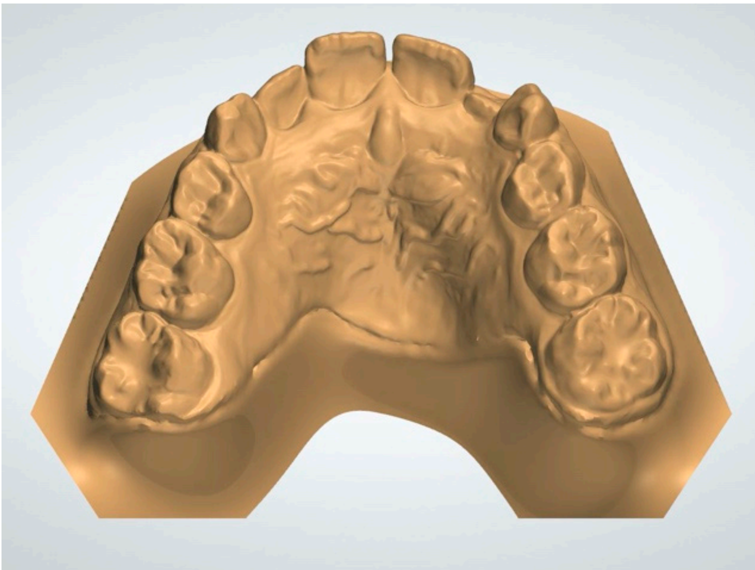

Figure 2. Dental model acquired through intra-oral scanning.

3.2. Elaboration of the Digital Model

The model acquired in digital format results in an open surface. Accordingly, it is not adequate for the subsequent printing. Before this phase, the digital model requires a "solidification" (consisting of the filling of the hollow spaces) or a thickening of its borders [1]. It is important to notice that the base of the digital model is not required to be as deep as that of the analogic one. Different current software is available for the digital model preparation.

3.3. 3D Printing

Once the digital model has been processed, the subsequent step is to produce a 3D object, reproducing, with the highest possible definition, the model acquired and elaborated. Nowadays, 3D printing for clinical uses is generally based on stereolithography and digital light processing (SLA/DLP), due to its high accuracy. More and more companies are developing new 3D printers with specific characteristics. Generally, the most important factors which distinguish each respective printer are the following: the surface area of the build platform size, the number of models printable per cycle, the printing resolution and speed, the variety of printable resins, the ease of use, and, inevitably, the cost [1].

3.4. Post-Printing Processing

This phase is extremely dependent on the 3D printing process, the material used and the printer manufacturer's indications. In particular, the post-printing process is required only for SLA technology but not for the other technologies. Generally, the model is washed for 10 min in isopropyl alcohol (IPA) 95% to remove the uncured resin [1]. Despite IPA being volatile, models must be air- or blow-dried to remove any residual of this compound. Subsequently, the model needs to be cured. Despite it is due to gradually harden when exposed to light, the model is generally exposed to UV light and heat. This assures a uniform polymerization in quick times. From now on, models are available to be handled without gloves [1].

3.5. Production of the Appliance

This stage consists of replication of traditional techniques for the production of orthodontic retainers and aligners, where a vacuum or pressure forming machine is employed to form the thermoplastic material exactly around the model. The main advantage of 3D printed models compared to the conventional plaster ones is represented by the fact that they are much less fragile and thus can be easily stored. Additionally, in case the working model is not available anymore, the entire process can be repeated with the final production of a new one starting from the original digital file. [1]

As regards the major applications of 3D printing, the production of working models represents a common application in the different specific fields of dentistry. Considering orthodontics, other applications are represented by the production of orthodontic retainers, activators, sleep apnea appliances, bites, customized lingual orthodontic brackets, Herbst appliance, occlusal splints, surgical templates for orthodontic miniscrews and miniplates placement. Other specific applications are related, for example, to prosthodontics (e.g., production of crown and bridge dentures, complete dentures, removable partial denture frameworks, etc.), oral implantology (e.g., production of custom trays and surgical guides for implants' positioning) and oral/maxillofacial surgery (e.g., for the production of occlusal splints, surgical implants, prostheses) [23,35].

Case reports showed that appliances fabricated using CAD/CAM technology perform, clinically, like conventional orthodontic appliances [36,37].

Figures 3 and 4 show a Rapid Palatal Expander (RPE) produced using a digital workflow encompassing the 3D printing.

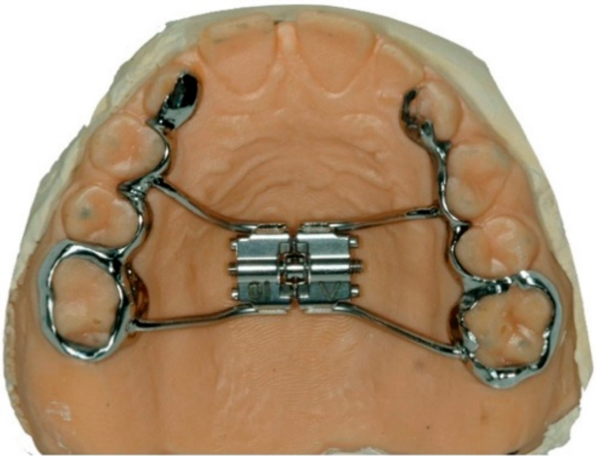

Figure 3. RPE welded to laser melting bands on a plaster model.

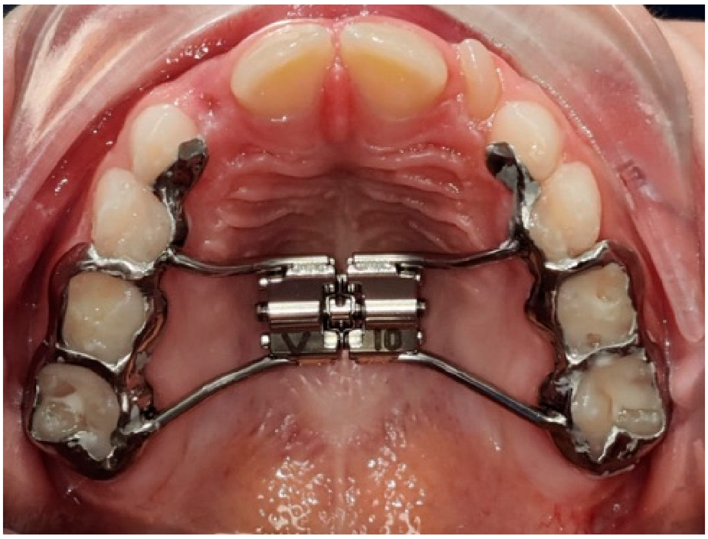

Figure 4. Clinical image of a cemented RPE.

Figures 5 and 6 respectively show the radiological planning for the placement of orthodontic miniscrews and the relative 3D printed surgical guide.

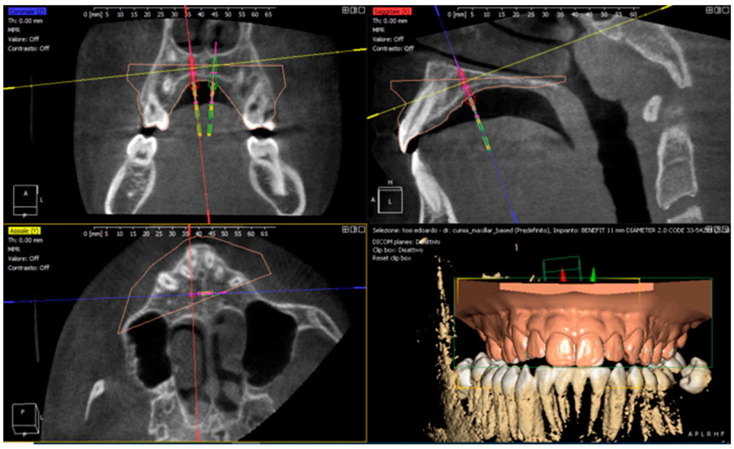

Figure 5. Three dimensional (3D) planning of a surgical guide for the placement of orthodontic miniscrews.

Figure 6. Three dimensional (3D) printed surgical guide for the placement of orthodontic miniscrews.

4. Advantages and Disadvantages of 3D Printing

Every technique, both traditional and innovative, is generally characterized by specific advantages and disadvantages which respectively promote and contrast the diffusion of the technique in question. Here is a summary of the pros and cons generally recognized for 3D printing [1,4,31–34,38–44].

4.1. Advantages

The advantages of the digital workflow and 3D printing are:

- Accuracy: while traditional models might undergo technical errors and distortions, 3D-printed models might be more accurate as they involve less steps and no manual labor.
- Comfort to the patient: the scanning process might be more comfortable for the patients than the traditional impression technique.
- Reduction of the times: due to the absence of analogic impressions, clinicians can directly send digital STL files to technicians, resulting in a digital workflow much more rapid compared to the traditional one.
- Management of defects: during the elaboration of the digital model acquired, eventual scan defects can be solved guaranteeing a correct progression towards the printing of a reliable product.
- Reduction of environmental costs: considering that traditional dental impressions are avoided by substituting them with STL file, the digital workflow inevitably reduces the numbers of materials which would require to be specifically disposed of. Accordingly, environmental costs are significantly reduced.

4.2. Disadvantages

The disadvantages of the digital workflow and 3D printing are:

- Costs: the expense for the purchase of the 3D printing and hardware are significantly higher compared to the analogic workflow.
- Longer learning curve: specific training is required for clinicians to familiarize themselves with the use of intraoral scanners to acquire a correct scanning guaranteeing a correct result of the entire process.
- The necessity of referral to specific technical laboratories: only laboratories with the available technologies required can be considered by clinicians working with a digital workflow.
- Health risk: specific procedures must be followed when handling uncured resins and cleaning solvents to avoid skin irritations caused by these materials. However, further aspects should be evaluated as regards the eventual toxicity of 3D-printed resins. In particular, monomer resins are recognized as toxic, despite their polymeric form generally are not.

5. Conclusions and Future Perspectives

The present review aims to highlight the potentiality of the digital workflow in dentistry, encompassing the use of 3D printing. In recent years, many more clinicians are facing a revolution in their clinical activity with a reduction that has gone through a significant change with a progressive transition from analogic towards digital dentistry. This requires an important familiarization with software and technologies for both dentists and dental technicians. Several advantages are linked to 3D printing, such as accuracy, patient comfort, shorter times and the reduction of environmental costs. Conversely, some disadvantages are still related to this technology (e.g., costs, longer learning curve, the necessity of referral to specific technical laboratories, and health risk), therefore further research should be performed to improve these shortcomings.

Based on this consideration, the digital workflow will likely go through a further expansion from a clinical point, and this not only in orthodontics but in almost every field of dentistry. Accordingly, future research should be conducted focusing on the mechanical properties of 3D-printed materials, to select the best-performing material for the specific application and further expanding the range of dental appliances that can be 3D printed for clinical use. In particular, in vitro tests should be carried out to compare both the microhardness and flexural strength of conventional materials and the respective 3D-printed version.

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