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Additive Manufacturing Technologies Used for Processing Polymers: Current Status and Potential Application in Prosthetic Dentistry

Marta Revilla-León, DDS, MSD [1,2] & Mutlu Özcan, DDS, DMD, PhD [3]

[1] General Dentistry Department, College of Dentistry, AEGD Texas A&M University, Dallas, TX
[2] Revilla Research Center, Madrid, Spain
[3] Dental Materials Unit, Center for Dental and Oral Medicine, University of Zürich, Switzerland

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Keywords
3D printing; additive manufacturing technologies; digital light processing; fused deposition modelling; material extrusion; material jetting; multijet printing; prosthodontics; stereolithography.

Correspondence
Marta Revilla-León DDS, MSD, 3302 Gaston Ave., Room 611, AEGD Program, College of Dentistry, Texas A&M University, Dallas, TX. E-mail: revilla@revillaresearchcenter.com

Marta Revilla León
http://orcid.org/0000-0003-2854-1135

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Abstract

There are 7 categories of additive manufacturing (AM) technologies, and a wide variety of materials can be used to build a CAD 3D object. The present article reviews the main AM processes for polymers for dental applications: stereolithography (SLA), digital light processing (DLP), material jetting (MJ), and material extrusion (ME). The manufacturing process, accuracy, and precision of these methods will be reviewed, as well as their prosthodontic applications.

Additive manufacturing (AM) technologies have vastly improved, allowing their integration into the digital workflow for prosthetic applications. AM technologies are the CAM technologies that consists of the fabrication of an object in a layer-by-layer building-up process.[1] The American Section of the International Association for Testing Materials (ASTM) International Standard Organization develops a voluntary consensus of technical standards for a wide range of materials, products, systems, and services. The ASTM committee F42 on AM technologies has named seven AM categories: stereolithography (SLA), material jetting (MJ), material extrusion (ME) or fused deposition modelling (FDM), binder jetting, powder bed fusion (PBF), sheet lamination, and direct energy deposition.[1] The current article reviews the main AM technologies used for polymer printing for dental applications.

Stereolithography (SLA)

SLA was conceived by Chuck W. Hull.[2-4] In SLA, the building platform is immersed in a liquid resin polymerized by an ultraviolet (UV) laser. The laser draws a cross-section of the object to form each layer. After the layer is polymerized, the building platform descends by a distance equal to the layer thickness, allowing uncured resin to cover the previous layer. This process is repeated a number of times until the printed object is built.[2-4] Almost at the same time of Hull's research, Prof. André prepared a different patent for SLA technology in France.[5,6]

Laser-based SLA 3D printing uses a UV laser to trace out the cross-sections of the object. The laser is focused using a set of lenses and then reflected off of two motorized scanning mirrors (galvanometer). The scanning mirror directs the precise laser beam at the reservoir of UV-sensitive resin to cure the layer (Fig 1). The depth of cure, which ultimately determines

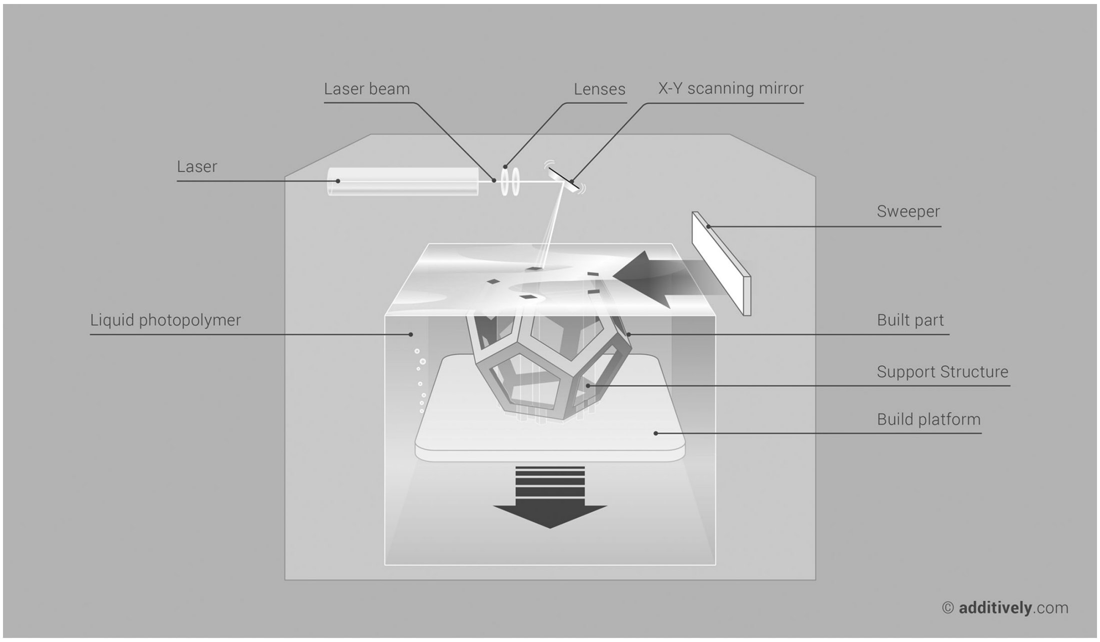

Figure 1 Stereolithography AM technology. Illustration courtesy of Additively.com.

the z-axis resolution, is controlled by the photoinitiator and the irradiant exposure conditions (wavelength, power, and exposure time/velocity) as well as any dyes, pigments, or other added UV absorbers.[7-9]

Generally, in the SLA process, the layer thickness depends on the printer model standards, which could range between 15 to 150 μm with a superficial roughness of approximately 35 to 40 μm Ra.[10] The wavelength range of the UV light that polymerizes the raw material depends on the printer, but it can range from 200 to 500 nm (Table 1).

One advantage of SLA technology is the temperature resistance and freedom of complex geometries that can print, whereas the main limitation is the necessity of support structures to manufacture objects. This consumes additional material and increases the production and postprocessing time.[11]

Digital light processing (DLP)

Larry Hornbeck of Texas Instruments created the technology for DLP in 1987.[12] The DLP AM is very similar to SLA technology, as it is considered the same AM category by the ASTM.[1]

The main difference between SLA and DLP is the light source, where the image is created by an arc lamp or by microscopically small mirrors laid out in a matrix on a semiconductor chip, known as a digital micromirror device (DMD). Each mirror represents one or more pixels in the projected image. The number of mirrors corresponds to the resolution of the projected image.[13]

A vat of liquid photopolymer is exposed to light from a projector under safelight conditions. The DLP projector displays the image of the 3D model onto the liquid photopolymer. In this system the physical object is pulled up from the liquid resin, rather than down and further into the liquid photopolymeric system. The radiation passes through a UV transparent window.[13] The process is repeated until the 3D object is built.[12,13]

Material jetting (MJ, PP)

The material jetting technology could also be called polyjet printing (PP), where a liquid resin is selectively jetted out of hundreds of nozzles and polymerized with UV light.[7] The UV-curable polymers are applied only where desired for the virtual design and, since multiple print nozzles can be used, the supporting material is co-deposited. Moreover, different variations in color or building materials with different properties can be designated, including the formation or structures with spatially graded properties (Fig 2).[15,16]

Material extrusion (ME, FDM)

Also called fused deposition modeling (FDM), this is a 3D printing method based on the extrusion of a thermoplastic material. Material is drawn through a nozzle, where it is heated and then deposited layer by layer. The nozzle can move horizontally, and a platform moves up and down vertically after each new layer is deposited (Fig 3).[17] FDM was first developed by Stratasys, founded by Scott Crump in the early 1990s.[18] The patents originally held by Stratasys have expired, resulting in dozens of FDM brands for the consumer market.

The FDM process has many factors that influence the final model quality, but it has great potential and viability when these factors are controlled successfully. While FDM is similar to all other 3D printing processes, as it builds layer by layer, it varies in the fact that material is added through a nozzle under constant pressure and in a continuous stream. This pressure must be kept steady and at a constant speed to enable accurate

Table 1 AM printers available on the market for dental applications

Brand	Technology	Printer	Light source	Min. layer thickness (μm)	Resolution (xyz)
3D systems (Rock Hill, SC)	SLA	ProJet 1200	UV Laser	30	56 μm (XY), 585 dpi
	MultiJet	ProJet MJP 3600 Dental	UV Laser	29-32	*UHD: 750 × 750 × 890 dpi
					*HDX: 375 × 450 × 790 dpi
					*HDP: 375 × 450 × 790 dpi
	SLA	ProJet 6000 MP	UV Laser	50-100	4000 dpi
BEGO (Bremen, Germany)	SLA	Varseo	UV Bulb (405 nm)	50-100	50 μm (XY)
		Varseo L	UV Bulb (405 nm)	50-100	60 μm (XY)
	DLP	Varseo S	UV LED (405 nm)	50-100	60 μm (XY)
Dreve (Unna, Germany)	DLP	**NA	UV LED	**NA	**NA
Envisiontec (Dearborn, MI)	SLA	VIDA	UV LED HD 1080 × 1920	25-150	73 μm (xy), 25–150 μm (z)
		VIDA Hi-Res	UV LED HD 1080 × 1920	50-150	50 μm (xy), 50–150 μm (z)
		VIDA Hi-Res Crown-Bridge	UV LED HD 1080 × 1920	25-150	35 μm (xy), 25–150 μm (z)
	DLP	DDDP	UV LED 1400 × 1050 Voxel size 71 μm	25-150	71 μm (xy), 25–150 μm (z)
Formlabs (Somerville, MA)	SLA	Form1+	UV Laser 405 nm, 120 mW	25, 50, 100, 200	NA
		Form2	UV Laser 405 nm, 250 mW	25, 50, 100, 200	150 μm (XY)
RapidShape (Heimsheim, Germany)	DLP (385 nm)	D30	UV LED HD 1080 × 1920	35, 50, 100	29 μm (XY)
		D40	UV LED HD 1080 × 1920	35, 50, 100	29 μm (XY)
Stratasys (Eden Prairie, MN)	PolyJet	Object30 OrthoDesk	UV Bul (200-400 nm)	30	600 × 600 × 900 dpi
		Object260/500 Dental	UV Bul (200-400 nm)	16, 28	*HQ: 600 × 600 × 1600 dpi.*HS: 600 × 600 × 907 dpi
		Object30 Dental Prime	UV Bul (200-400 nm)	16, 28	
		ObjectEden 260VS	UV Bul (200-400 nm)	16, 28	

*UHD: ultra-high definition, HDX: high-definition smooth, HDP: high-definition plaster; HQ: high quality, HS: high speed. **NA: not available.

results.[19] Material layers can be bonded by temperature control or through the use of chemical agents.

Additionally, the nozzle that deposits material will always have a radius, as it is not possible to make a perfectly square nozzle, and this will affect the final quality of the printed object.[20] Accuracy and speed are low when compared to other processes, and the quality of the final model is limited to material nozzle thickness.[21] When using the process for components where a high tolerance must be achieved, gravity and surface tension must be accounted for.[19] Typical layer thickness varies from 0.178 to 0.356 mm.[22]

Manufacturing process

The complete process of manufacturing an object with a 3D printer involves the following sequence: data acquisition, data processing, additive fabrication, and post-processing procedures.[15,16]

- Data acquisition can be performed by either non-contact or contact scanning devices. The most common techniques used are computerized tomography (CT), cone beam computed tomography (CBCT), magnetic resonance imaging (MRI), and laser digitizing (extraoral or intraoral scanning devices) (Fig 4).
- Data processing involves the virtual design of the object using specific CAD software (Fig 5). When the design of the object is completed, the STL file is imported on the printer software, where the build variables and parameters for slicing and adding the support structures to generate the information needed for control of the 3D printer are specified (Fig 6).

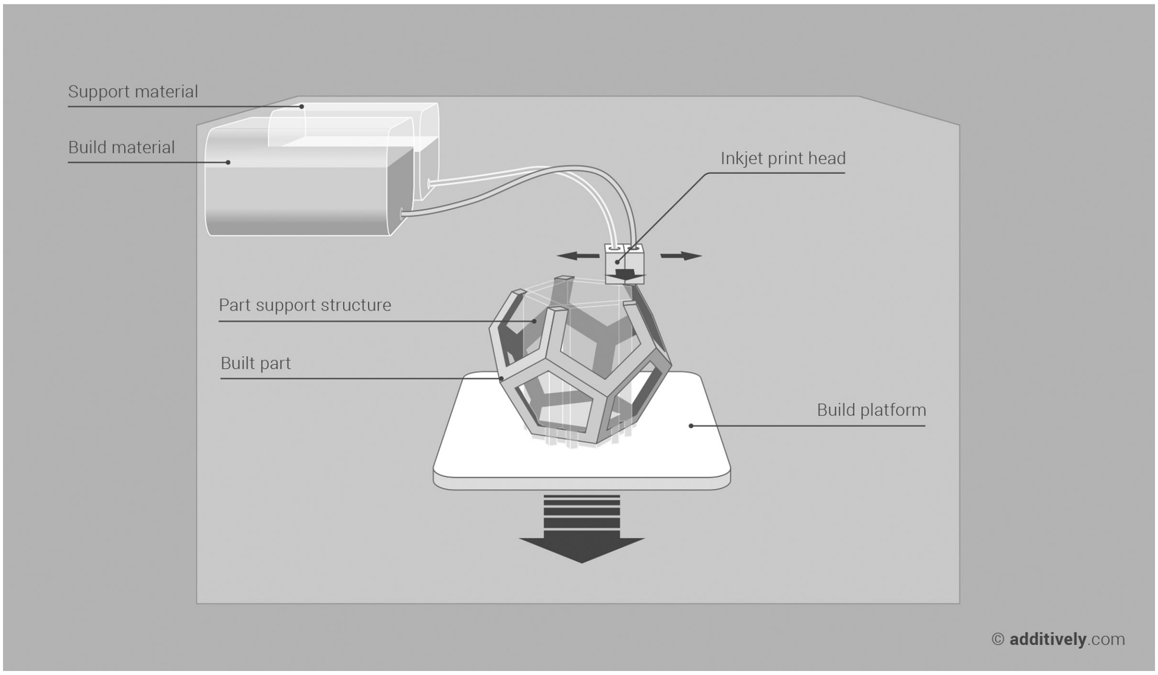

Figure 2 Material jetting 3D printing technology. Illustration courtesy of Additively.com.

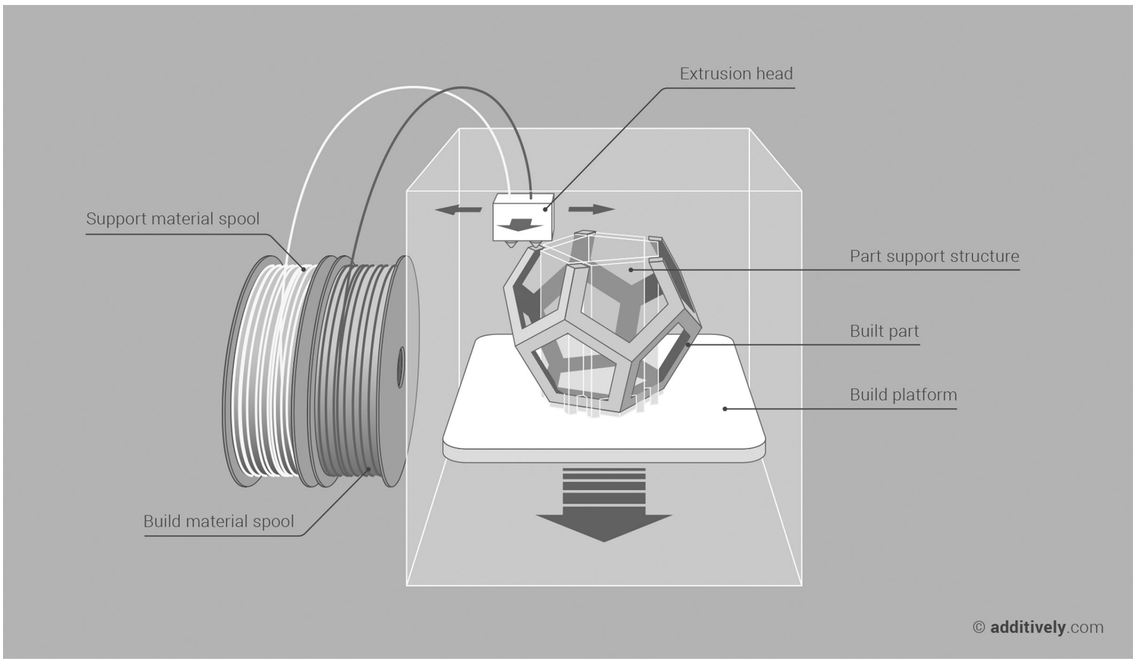

Figure 3 Material extrusion or FDM AM technology. Illustration courtesy of Additively.com.

- Additive fabrication means building the object using the slice file on the 3D printer (Fig 7AB).
- Post-processing, cleaning the object, and post-curing to complete the polymerization process (Fig 7C-F): each technology and printer will have its own post-processing recommendations provided by the manufacturer.

Resolution, accuracy, and repeatability of SLA, DLP, MJ, and FDM

The distinction between resolution, precision, and trueness needs to be clarified. *Resolution* is the finest or smallest feature that the 3D printer can reproduce, specific for each technology

Table 2 Material available for AM printers approved for dental applications

Brand	Name	Definition provided	Wavelength (nm)
3D Systems (Rock Hill, SC)	VisiJet FTX Green	Tough castable plastic	405
	VisiJet FTX Cast	Wax and plastic hybrid	
	VisiJet M3 DentCast	Wax-up castable material	
	VisiJet FTX Cast	Wax-up castable material	
	VisiJet FTX Green	Wax-up castable material	
	VisiJet M3 PearlStone	Solid stone appereance	
	VisiJet M3 StonePlast	USP Class IV capable, translucent or stone finish	
	VisiJet M2R-TN	Models, tan color	
	VisiJet SLe-Stone	High-Contrast color, dental stone	
	VisiJet SL Clear	USP Class VI capable, crystal-clear appearance, polycarbonate-like	
	Accura e-Stone	High-contrast color, dental stone	
	Accura ClearBlue	USP Class VI capable, crystal-clear appearance, polycarbonate-like	
BEGO (Bremen, Germany)	VarseoWax Splint	Occlusal splint, clear	405
	VarseoWax SG	Surg. guide, transparent blue	
	VarseoWax CAD/Cast	Castable, opaque yellow	
	VarseoWax Tray	Custom trays, opaque blue	
	VarseoWax Model	Model, yellow-brown	
DeltaMed (Friedberg, Germany)	3Delta Model	Models, apricot color	385-405
	3Delta Model Ortho	Orthodontic devices, beige color	
	3Delta Cast	Castable, brown color	
	3Delta Cast P	Castable, orange color	
	3Delta Guide	Surgical guides	
Detax (Ettlingen, Germany)	Freeprint cast	Castable, red color	LED UV 405 or 378–388
	Freeprint tray	Custom impression trays	
	Freeprint splint	Splints, surgical guides	
	Freeprint Temp	Provisional restorations. Color A1, A2, A3	
	Freeprint model	Models; Color: ivory, grey, sand	
	Freeprint model T	Models for the thermoforming technique; Color: light blue	
	Freeprint ortho	Orthodontic devices; Color: Clear	
Dreve (Unna, Germany)	FotoDent Model	Model, opaque beige	405
	FotoDent Tray	Custom impression trays	
	FotoDent Guide	Surgical guides	
	FotoDent Gingiva	Gingiva for models	
Envisiontec (Dearborn, MI)	E-apliance/3SP/M	Ortho appliances	365-405
	3SP	Models, peach	
	Ortho Tough 3SP/M	Ortho models aligners, pink	
	E-DentStone/M	Models	
	ClearGuide/M	Surgical guides, clear	
	E-Guard	Occlusal splints, clear	
	E-Partial	Castable, RPD	
	E-Dent/M	Microfilled provisionals. Color A1, A2, A3	
	Press-E-Cast/M	Castable, yellow	
FormLabs (Somerville, MA)	Dental SG	Surgical Guides, clear	405
	Dental Model	Models	
	Dental LT Clear	Splints, retainers, or orthodontic devices	
	Castable	Castable	
	Grey Resin	Models, trays	
Nexdent (Soesterberg, Netherlands)	Base	Denture Base, pink	Blue UV-A (315-400) + UV-Blue (400-550)
	SG	Surgical Guide, transparent	
	C&B	Crowns & bridge, Class IIa	
	C&B MFH	C&B Micro-filled hybrid, Class IIa	
	Ortho Clear	Splint & retainers, Class IIa	
	Ortho IBT	Ortho applications, Class I	
	Ortho Rigid	Splints, Class IIa	
	Model	Dental models, ochre	
	Model Ortho	Dental models, beige	

(Continued)

Table 2 Continued

Brand	Name	Definition provided	Wavelength (nm)
	Tray	Tray, Class I, blue and pink	
	Gingiva Mask	Gingiva mask models, pink	
	Cast	Castable material, purple	
Shera (Lemförde, Germany)	SheraPrint gingiva mask	Gingiva masks for models	NA
	SheraPrint	Models, splints, trays, surgical guides	
Stratasys (Eden Prairie, MN)	Clear-Bio (MED610)	Clear biocompatible	200-400
	VeroGlaze (MED620)	A2 color, provisional up to 24 h	
	VeroDent (MED670)	Models	
	VeroDent Plus (MED690)	Models	

*NA: not available.

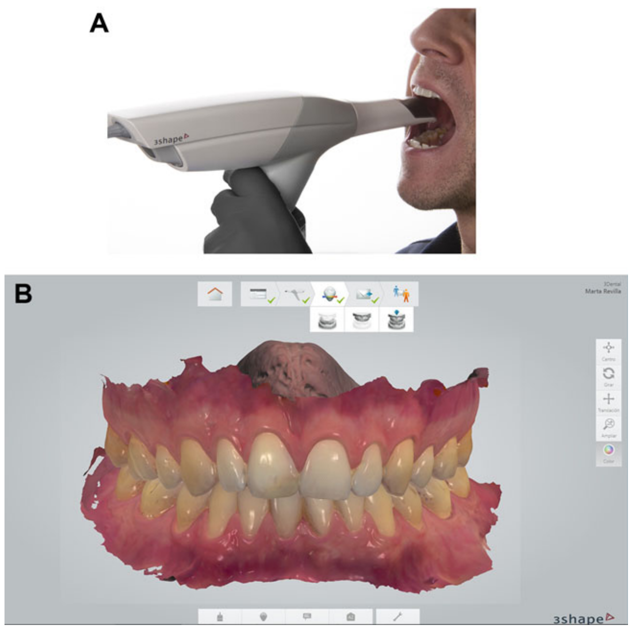

Figure 4 A, Data acquisition with an intraoral scanner device (TRIOS 3 Color Pod; 3Shape, Copenhagen, Denmark); and B, Digital impression of the maxillary, mandibular, and interocclusal record completed with the intraoral scanner device. A data mining extensions (DMX) file is created.

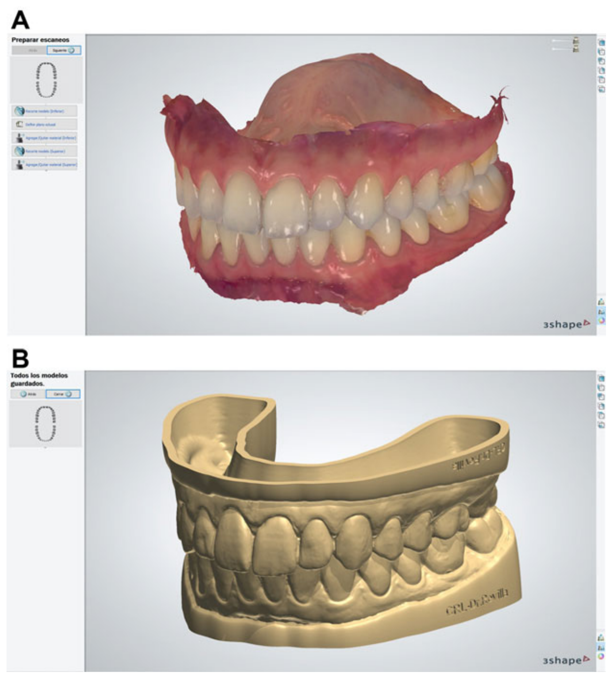

Figure 5 Data processing example from the data acquisition with an intraoral scanner to the virtual design of the diagnostic models. A, The DMX file created from the digital impression is imported into the specific CAD software (Dental System; 3Shape); and B, Specific dental CAD software (Model Builder, Dental Systems; 3Shape) was used to create the STL file of a virtual maxillary and mandibular model.

and printer (Table 1). The resolution of a 3D printer should be defined on each x, y, and z-axis in μm or dots per inch (dpi), where the z-axis corresponds normally to the layer thickness. *Precision* or *repeatability* is the ability of a 3D printer to manufacture objects with the exact same 3D dimensions, or how close repeated printed objects are to each other. *Trueness* refers to the discrepancy between the printed object and actual dimensions of the desired object.[23]

In the dental digital workflow, discrepancies can be incorporated with each step. Moreover, the technology selected, the 3D printer used, as well as the material chosen for the AM of the desired object make a difference (Tables 1 and 2). Not all printers that manufacture an object with the same technology present the same resolution capabilities. So, each printer has a determined resolution, which is provided by their manufacturer. Moreover, each material has its own activation range wavelength, power, and exposition time for their manufacturing on 3D printers. Therefore, not all AM materials are compatible with all AM printers. Furthermore, the manufacturer´s post-processing procedures need to be carried out carefully to avoid further distortions of the printed object.

Different factors, such as laser speed, intensity, angle and building direction,[22-27] number of layers,[22] software,[27] shrinkage between layers,[25] amount of supportive material[24] and post-processing procedures, can affect the accuracy (precision and trueness) of the printed object. Because of the disparities in the protocols, technology selected, and parameters of the printers

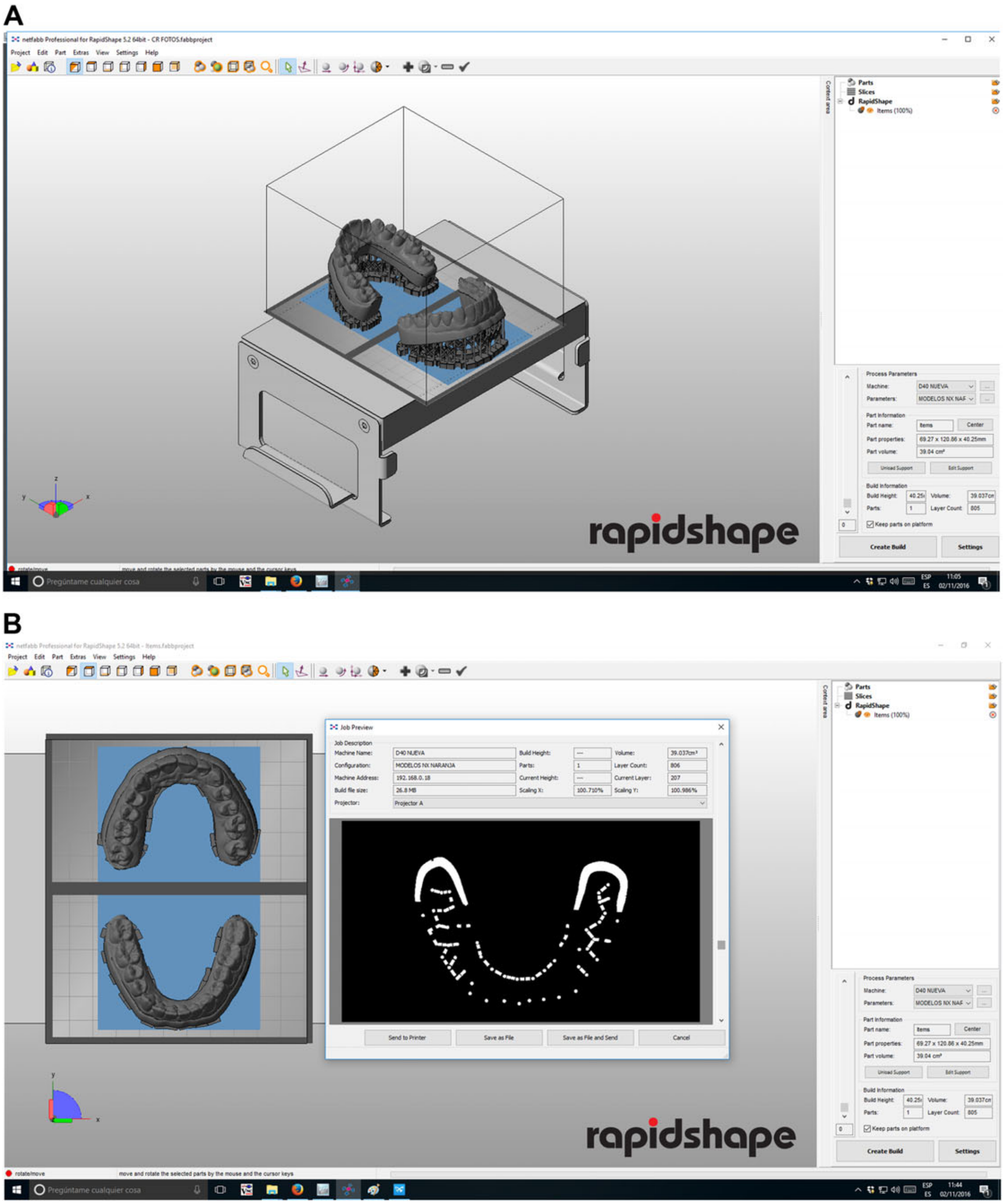

Figure 6 Data processing by the specific printer software (D30 RapidShape) for the objects. A, Positioning and orientation on the building platform and; B, Slicing, adding the supportive structures, and volume calculation of the polymer resin needed.

and the 3D polymer printed material used, it is very difficult to compare the results obtained in different studies.

Alharbi et al[24] evaluated the effect of the printing building direction on the mechanical properties of cylinder-shaped hybrid composite resin printed specimens. Vertically printed specimens with the layers oriented perpendicular to the load direction presented significantly higher compressive strength than horizontally printed specimens with the layers oriented parallel to load direction.

Brain at al[25] studied the manufacturing tolerance of four polymer AM printers (Formiga P110 from EOS, Projet MP 3510 from 3D Systems, Objet 30 and Object Eden from Stratasys) following the manufacturers' parameters. Two geometries were analyzed. The AM material was selected based on the print resolution, specification of the production unit, software, and manufacturing time. Only two of the four printers used the same AM material. Differences in production tolerance were

Figure 7 Example of the AM process using a DLP printer (D30 RapidShape). A, DLP printer manufacturing dental models; B, Building platform with the AM casts just printed; C, after the removal of the printed objects of the building tray, the AM objects are submerged in an cleaning solution (isopropyl 96%) for 4 minutes to remove the nonpolymerized resin; D, The models are placed inside a UV-light lamp (Otoflash, BEGO) to complete the light cure of the AM model; and, E, Removal of the supportive structures. [Color figure can be viewed at wileyonlinelibrary.com]

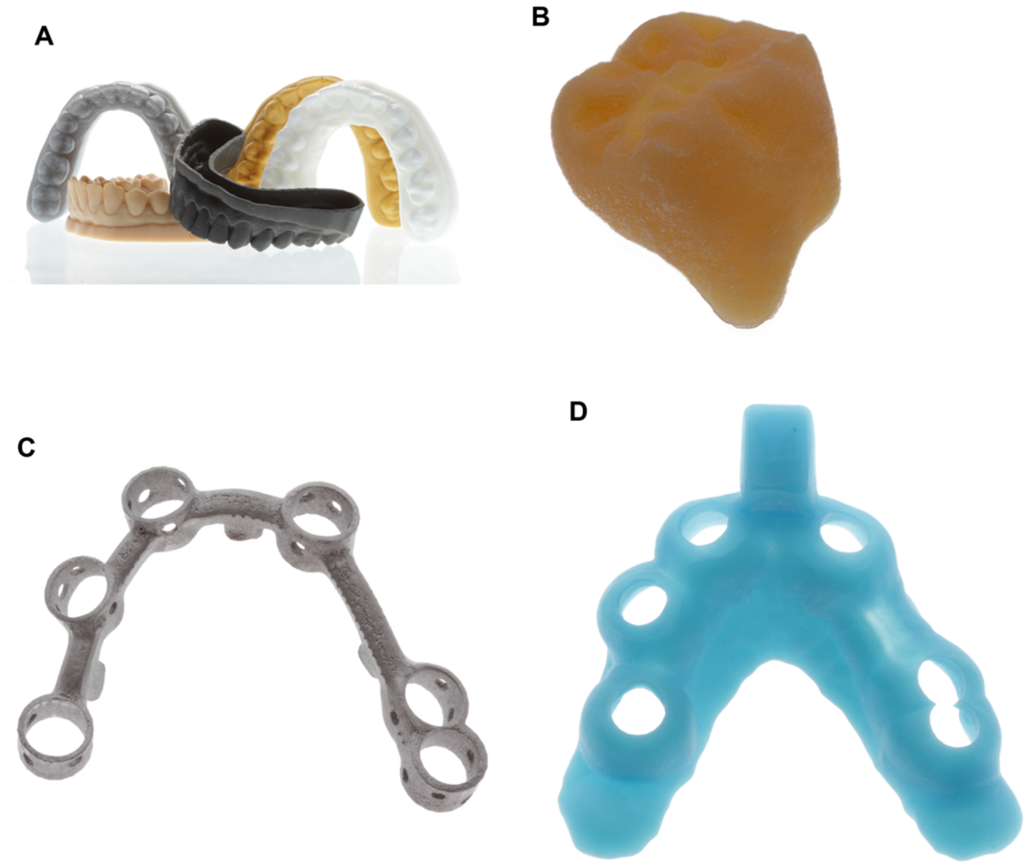

Figure 8 Examples of different applications of polymer AM technologies for dentistry; A, AM dental casts fabricated with different technologies and polymers; B, 3D-printed castable pattern of a full coverage restoration; C, 3D-printed metal framework for a complete-arch implant impression; and D, AM custom tray for a complete-arch open tray implant impression.

found between the different printers and technologies analyzed. The results showed an accuracy from -61 to 92 μm.

Ide et al[26] analyzed the capacity of 3D printers to reproduce acute angles (60°, 45°, 30°, 20°, 10°, and 5°) considering the building printing direction on six triangular prism-shaped specimens using one polyjet and two FDM AM printers. Each printer used a different AM material. They concluded that the dimension production tolerance of the printers of geometry analyzed was less than 1.00 mm in all the x-, y-, and z-axes, but the acute angles could not be reproduced precisely.

Prosthodontic applications

There are a wide variety of available polymers for prosthodontic applications of 3D printing, such as printed casts (diagnostic casts, definitive casts for tooth-borne prostheses, definitive casts for implant-borne prostheses), complete dentures, printed castable patterns for cast or pressed restorations, or custom impression trays.

Printed casts

One of the first applications of AM technology was the materialization of the digital impression to obtain printed casts for diagnostic purposes or definitive casts to deliver a tooth- or implant-borne fixed dental prosthesis (FDP) (Fig 8A). For prosthodontic applications, where a digital impression is made, the most reasonable workflow includes two options for the manufacturing of the tooth-borne FDP: a milled monolithic full-contour restoration or a milled or AM framework with a posterior ceramic application. With the first option, the marginal and internal fit, contact point, and occlusal contact are defined in the STL file of the restoration's virtual design. Its accuracy is the accumulation of the distortion from the digital impression, the parameters determined on the design software, and the CAM processes to manufacture the restoration. In this case, fabrication of the definitive cast can be avoided. On the other hand, with the second option only the marginal and internal fit are determined on the virtual design on the restoration. So, the manufacturing of the definitive cast is a necessary step to finish the restoration for the ceramic application where the contact point and occlusal contact will be created.

Extraoral digitalization of the diagnostic cast for orthodontic purposes has been widely analyzed.[28-32] Published studies have reported that the digital models are as reliable as traditional plaster casts, with high accuracy, reliability, and reproducibility; however, the reported limitation of extraoral digitalization is landmark identification, instead of the measuring system or the software employed.[31,32]

The intraoral digitalization of the patient´s mouth and the AM of the STL file obtained has also been evaluated.[33-37] In 2014, Patzelt et al[33] digitalized a dental model with a laboratory scanner as a reference and three intraoral scanners (Lava Chairside Oral Scanner C.O.S, CEREC AC Bluecam, iTero) from which 3D-printed (SLA technology for the LAVA C.O.S and CEREC Bluecam digital impression) or milled (for the iTero digital impression) casts were manufactured and re-scanned with the same laboratory scanner. Patzelt et al used specific CAD software to superimpose the cast. The trueness values reported for Lava C.O.S., iTero, and CEREC AC Bluecam were 38, 49, and 332.9 μm, respectively; and the precision values were 38, 40, and 99 μm, respectively. Moreover, the SLA-based casts presented a higher accuracy than milled casts.

Hazeveld et al[35] investigated the accuracy and reproducibility of physical dental casts reconstructed from digital data by three AM techniques: DLP, MJ, and a powder-based polymer (PBP) printer. The mean systematic differences for the measurements of the clinical crown heights were 40, -20, and 40 μm for the DLP, MJ, and PBP printed casts, respectively. For the width of the teeth, the mean systematic differences were -50, 80, and -50 μm for the DLP, MJ, and PBP groups. The dental models manufactured with the CAM tested could be a reliable option for orthodontic purposes; however, it may not be enough accuracy for prosthodontic applications.

When an implant-borne prosthesis is delivered through the digital workflow, the same two options mentioned above for the tooth-borne FDP are likely. To the best knowledge of the authors, there is no report of the clinical adjustments needed for the first and second options mentioned above for tooth- or implant-borne FDP, or studies that evaluate the accuracy of AM definitive casts for both tooth- and implant-borne FDP.

Revilla-León et al[37] analyzed the position accuracy of implant analogs on 3D printed polymer versus conventional dental stone casts measured using a coordinate measuring machine (CMM). AM technologies evaluated were capable of duplicating a conventional definitive implant cast with the same accuracy of conventional procedures.

Complete dentures

The development of digital systems allows the manufacturing of complete dentures (CD) through CAD/CAM procedures[38-47] where a denture base can be milled or both the denture base and the denture teeth can be milled in one piece.[41,42,45,46] Maeda et al[40] published the first scientific report in English where CAD/CAM was described to fabricate a CD. Digitalization of the conventional impression was followed by the CAD design of the CD. The manufacturing of the denture base or the whole CD was described by either a milling process or a SLA 3D printer.

Sun et al[46] described a technique that combined analog and digital procedures, where the individual flasks were fabricated using AM. The digitalization of the conventional working edentulous maxillary and mandibular casts, wax rims, and maxillomandiular record was completed with an extraoral scanner. Software was developed by the authors and used to set up the denture teeth, and to design the artificial gingiva, the baseplate, and the virtual flasks.

In 2015, Bilgin et al[47] described a combination of conventional and digital procedures where the DLP AM technology was used to fabricate the denture teeth in one piece with a micro-hybrid nano-filled resin. Similar to previous authors, the digitalization of the working edentulous plaster casts mounted on the articulator and the wax rims was obtained using a laboratory dental scanner.

Inokoshi et al[48] compared the tooth try-in for a maxillary and mandibular CD obtained from conventional and AM technologies on ten patients. With conventional procedures, a baseplate and denture teeth wax-up were prepared and digitalized using a CBCT. A complete denture tooth try-in design was completed using CAD software and manufactured using a polyjet 3D printer. According to patient ratings, both techniques were evaluated equally in terms of esthetics, predictability of final denture shape, stability, comfort of the dentures, and overall satisfaction; however, from the prosthodontists' rating, chair time, try-in stability, and overall satisfaction were significantly higher with the AM than with the conventional method.

When manufacturing a CD, a complete digital workflow includes the digital impression of the completely edentulous arch, including challenging areas for the intraoral devices like the registration of mobile areas such as the non-keratinized tissue or smooth surfaces covered by saliva.[39,40] Patzelt et al[38] developed an in vitro study to analyze the capability of intraoral scanners to reproduce accurate edentulous arches. The authors concluded that these digital impressions appear to be feasible, although the accuracy of the scanners differs significantly. The results of this study showed that only one scanner was sufficiently accurate to reproduce the edentulous jaw; however, the master edentulous cast used on this in vitro study is a silicone model that may not precisely represent the clinical oral conditions.

Bidra et al's systematic review[43] concluded that the use of computer-aided technology to fabricate CDs has been studied since 1994 by multiple investigators using CAD/CAM as well as rapid prototyping methods. Significant advancements in this technology have been made since its inception, but currently no clinical trials or clinical reports are available in the scientific literature.

Printed castable patterns

Multiple castable polymers are available for the different 3D printing technologies (Fig 8B). These polymers can be processed through conventional procedures and thus, cast metal or pressed lithium disilicate restorations can be obtained.[49-60] Williams et al[50] reported the first dental CAD/CAM clinical case description for fabricating a castable 3D printed pattern for a metal framework of a removable partial denture (RPD). The digitalization of the master cast was completed with an extraoral scanner, the undercuts were electronically identified on surveyed virtual casts, and the RPD was digitally designed with CAD software. The castable pattern was cast through conventional procedures. Later, a technique for the Co-Cr RPD framework manufacturing using metal AM technologies was reported.[51,52]

Kattadiyil et al,[53] in a clinical report, described a technique that combined analog and digital procedures for RPD fabrication. The digital impression was made with an intraoral scanning device (iTero; Cadent) to obtain the virtual master cast. A total of 56 scans were needed to capture the maxillary and mandibular arches and the interocclusal record and another 25 scans for the rest seats. The RPD framework was created using CAD software and manufactured additively. The RPD was finished using conventional procedures.

A castable printed pattern can be also used to manufacture pressed lithium disilicate ceramic restorations; however, to the best knowledge of the authors, only a few studies have evaluated the marginal and internal fit considering the fabrication method of the patterns (handmade, milled, or printed). Fathi et al[57] measured the internal and marginal gap of the crowns fabricated from handmade, milled, and AM patterns using the replica and sectioning technique. The restorations presented a clinically acceptable marginal gap between 111 ± 28 and 126 ± 43 μm. Furthermore the crown obtained from a 3D-printed pattern showed a significantly better marginal and internal gap in both measurement techniques.

Mai et al[58] analyzed the marginal and internal gap and the accuracy of the proximal contact of the crowns fabricated from three manufacturing processes: compression molding, milling, and 3D PP technology (Object Eden; Stratasys). The fit was evaluated with the silicone replica and the image superimposition techniques. No differences were found on the proximal point obtained between the three techniques; however, the compression molding technique also presented specimens with a deficient proximal contact. The smallest absolute marginal gap was obtained on the 3D PP group (99 ± 19 μm), and the highest was for the molding group (163 ± 86 μm). Moreover, the 3D PP group presented a better internal gap, being most evident at the occlusal measurement. Kim et al[59] evaluated the reproducibility and marginal discrepancy of resin copings fabricated using a SLA printer by repeating 1, 3, or 6 arrays to give a total of 18.

Custom impression trays

Custom trays can be also manufactured through AM technologies (Fig 8C, 8D).[61,62] The CAD design of the custom tray allows the control of a homogeneous space for the impression material and reduces the manual procedures. The fabrication of 3D-printed custom trays for a completely edentulous patient[59,60] and for a complete-arch implant impression technique[61] has been previously reported. Nevertheless, this manufacturing process can be used in any clinical procedure where a custom tray is needed.

Conclusions

The integration and development of protocols for a complete digital workflow are still needed. A promising future is ahead for the prosthodontic applications of the AM technologies, where a complete digital workflow could be systematically applied in our daily work.

The continuous development and improvement of AM technologies are unstoppable as is the variety of materials that can be printed. The future is challenging our dental needs. The main challenge, in the opinion of the authors, could be to face the rapid obsolescence of the new technologies that require an important economic investment for dental laboratories and private practices, the complete digital integration that requires different methodologies caused by the different tools, where a learning curve is expected, and the resistance to change when incorporating new processes because of the command of the conventional ones.

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