Additive Manufacturing Technologies: Where Did We Start and Where Have We Landed? A Narrative Review

Nawal Alharbi, BDS, MSc, PhD
Department of Prosthetic Dental Sciences, College of Dentistry, King Saud University, Riyadh, Saudi Arabia.

Reham B. Osman, BDS, MSc, PhD
Prosthodontics Department, Faculty of Dentistry, Cairo University, Cairo, Egypt.

Additive manufacturing (AM), also known as 3D printing, is gaining burgeoning interest among various dental disciplines. The import of this technology stems not only from its ability to fabricate different parts but from the solutions it provides for the customization and production of complex designs that other methods cannot offer—all to the end of enhancing clinical treatment alternatives. There is a wide range of AM machinery and materials available to choose from, and the goal of this review is to provide readers and clinicians with a decision tool for selecting the appropriate technology for a given application and to successfully integrate AM into the digital workflow. *Int J Prosthodont 2024;37(suppl):s243–s252. doi: 10.11607/ijp.8828*

Additive manufacturing (AM), also known as 3D printing, is one of the fundamental components of the fourth industrial revolution.[1] Since the emergence of the technology back in 1980s, it has received a growing interest within the automotive, aerospace, and medical fields.[2–4] Initially, the technology was used to fabricate architectural and conceptual models to appraise design concepts.[5] Simultaneous with developments in digital technologies and material sciences over the last years, there has been substantial development in AM technology and its applications for the fabrication of different functional parts.[6] The integration of 3D printing into the dental field over the past 10 years is indisputable.[7,8]

By fabricating objects layer by layer, AM allows more flexibility and freedom in designing and manufacturing complex shapes. It offers an innovative, cheaper, and faster

Correspondence to:
Dr Nawal Alharbi,
nalharbi@ksu.edu.sa,
nawalmurshed@gmail.com

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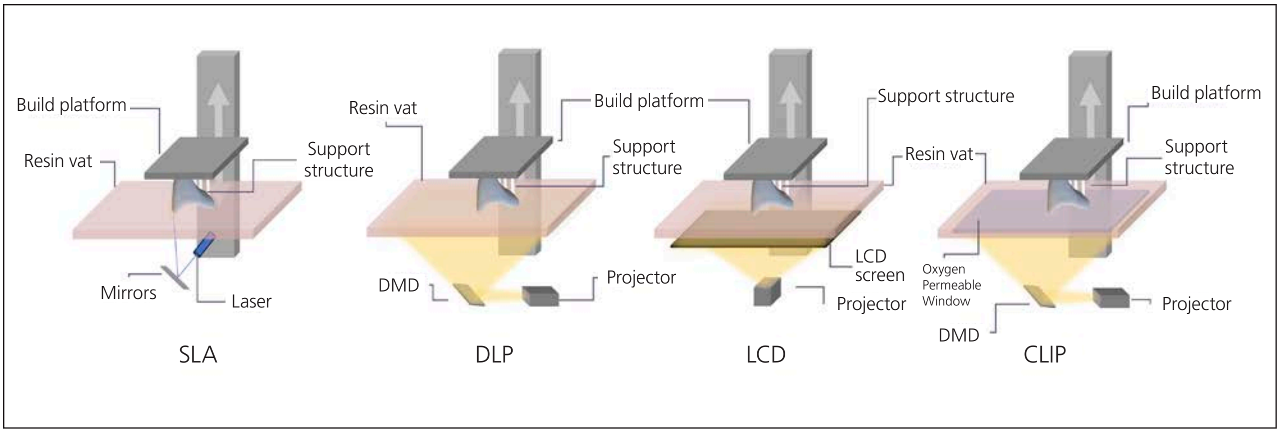

Fig 1 Various vat photopolymerization AM techniques.

alternative for the fabrication of dental parts compared to milling technology. It also avoids the limiting factor of milling bur size, which boosts the ability for on-demand production. Additionally, there is no limit to the size of the printed object, in contrast to the standard-sized material blocks used in milling techniques.

Standing the test of time, the technology of 3D printing, has captured the interest of the scientific community, including dentists and dental technicians, as reflected by the rapid increase in the number of published works between 2014 and 2023. The technology has proved itself in terms of accuracy and precision for various dental applications, including study models, orthodontic appliances, surgical guides, mock-ups, provisional restorations, and recently, definitive restorations. Several previously published reviews have covered AM techniques, the most prominent being the one by Alharbi et al,[7] which covered all available techniques and their dental applications up to 2016, as well as the involved printing parameters.

Continuous development in 3D printers and dental materials has made it possible for companies to fuel the dental field with numerous printers and a wide variety of materials to choose from. This makes it hard to know where to start, both for novice and experienced users. This review is intended to provide a decision tool for selecting the appropriate technology for a given application and to successfully integrate AM into the digital workflow.

AM TECHNOLOGIES

AM is the process of building objects layer by layer directly from a raw material. The mechanism of joining/bonding the layers varies between different AM techniques. According to International Organization for Standardization/American Society for Testing and Materials (ISO/ASTM) F2792,[9] AM technologies are categorized into seven groups, including binder jetting, directed energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination, and vat photopolymerization (the most common technique used in the dental field). The 3D printers on the market differ both in the method used for joining the layers and in the nature of the material used by each printer. In the following section, the AM technologies most commonly used in the dental field are highlighted.

VAT PHOTOPOLYMERIZATION

Vat photopolymerization technology, including but not limited to stereolithography (SLA) and digital light processing (DLP) techniques, is the most common AM technique used in dentistry (Fig 1). It involves using a curing source to polymerize a photopolymerizable resin.[10]

The SLA technique was originally developed by Charles Hulls in 1980 and marketed by 3D-Systems in 1983. With SLA, a spot laser source is used to trace the 2D–cross-section of the model and polymerize the resin in each layer. The basic element of the technology is polymeric resin material in the vat/tank and a moving build platform where the printed part is fabricated and attached. During the printing process, the build platform is elevated so that a thin layer of the resin can flow onto the surface of the tank, the build platform is dipped in the resin, and the second layer is created in the same pattern. The process is repeated until the model is completed. Tilted stereolithography (TSLA) has recently been introduced in chairside printers as a modified form of SLA in which the build platform is tilted and the resin material runs through the build process. The tilted platform allows for printing with highly viscous materials, such as resin-infiltrated ceramics with multi-shade properties, in addition to conventional printable resin materials.[11,12]

DLP technology differs from SLA in its light source, which consists of a digital light projector to project a single image on each layer. The image is the 2D–cross-section of the model in the form of pixels. The light irradiated from the projector to the build platform is controlled by a digital micromirror device (DMD). Because the entire build platform is exposed at once, the process is faster than SLA.[13] A developed version of DLP technology on the market is continuous liquid interface processing/digital light synthesis (CLIP/DLS). In CLIP/DLS, a dead zone is created via the addition of an oxygen-permeable window within the build platform, which permits a continuous flow of resin during the printing process. It is claimed that CLIP/DLS can be used to achieve layerless resin parts as the interfaces between layers are omitted. This results in improved mechanical properties and significantly shortens the print time compared to conventional DLP/SLA techniques.[10] Liquid crystal display (LCD) is another variant of DLP technology that has emerged during the last few years. It uses an LCD as a curing source and is cheaper than DLP and SLA techniques, probably with a shorter print time.

Another printing technique to fabricate resin parts is the jetting/PolyJet technique, in which the material is jetted onto the platform and cured with UV light, allowing for the production of multicolor parts.[7]

Several factors influence the accuracy and precision of vat photopolymerization technology.[14] The main factors in SLA technology are the laser spot size, the intensity and speed of the laser, the quantity of monomer, and the number of photoinitiators in the resin. Additional factors to consider with DLP, CLIP, and LCD technologies are the pixel size, the quality of the light source, and the build platform size.[10] Spot-curing the printable resin in the SLA technique yields more accurate printed parts compared to layer projection–curing in the DLP technique.[15] In the DLP technique, the pixel size/resolution of the projector influences accuracy and precision, where decreasing the pixel size enhances the accuracy and precision of the printing process.[14,16] Alharbi et al[17] and Osman et al[18] evaluated the dimensional accuracy of full-coverage restorations fabricated using SLA and DLP techniques. The results revealed that the SLA 3D-printed restorations offered improved dimensional accuracy compared to the DLP technique. Similarly, Kim et al[19] showed that SLA-fabricated crowns had better accuracy than their counterparts fabricated using DLP and milling techniques.

Unkovskiy et al[20] compared the accuracy of complete denture bases fabricated using SLA and DLP techniques. The SLA denture bases had higher trueness values than the DLP denture bases. Similarly, some authors have shown that improved accuracy of printed models can be achieved with the SLA technique.[21] On the other hand, Yoo et al[22] demonstrated comparable accuracy between models fabricated using SLA and DLP techniques when used for the fabrication of three-unit prostheses. When considering the DLP vat photopolymerization printing technique and its variants, Moon et al[23] showed that DLP provided better dimensional accuracy than LCD when used for printing single-unit provisional restorations. However, increasing the span length of the prosthesis decreases the accuracy of the printing process with DLP. L'Alzit et al[24] evaluated the influence of fabrication technique and model size/extension on the accuracy of printed surgical guides. The results showed that model size/extension rather than the fabrication technology influences the dimensional accuracy of the surgical guides. No difference was observed in the accuracy levels between SLA, DLP, and PolyJet techniques. Large extent guides exhibited lower accuracy compared to smaller-sized guides.[24]

Thus, depending on the intended clinical use, a particular printer can be selected over another. When esthetics, details, and dimensional accuracy are critical, SLA and CLIP are the techniques of choice. When speed and cost are prioritized, DLP and LCD are the better options. Other influencing factors that govern printer selection include the availability of the material that is calibrated and can be used with a given printer.

There are two main essential requirements needed for the material to be used with the vat photopolymerization technique. The material should be photopolymerizable and should have sufficient viscosity that can allow a quick flow of the layer without any assistance. Polymeric resin material is the most commonly used material with different vat photopolymerization techniques. Initially, with the emergence of dental 3D printers, poly methyl methacrylate (PMMA) was used to fabricate study models, mock-ups, and provisional dental restorations with sufficient accuracy. Printing provisional restorations was possible only with a single shade material. Transparent PMMA was then introduced to fabricate surgical guides and occlusal devices. More recently, with the development of a new family of printable polymeric materials with improved physical and mechanical properties, the fabrication of definitive restorations with 3D printing has become possible. Currently, with constant ongoing modifications, printing of multi-shade definitive restorations became possible contrary to the initial sole availability of single-shade printed provisional restorations.

Zirconia and ceramic materials can be used with the vat photopolymerization AM technique when mixed with polymeric binders[25–27] (Fig 2). An additional post-processing step is necessary to eliminate the binder and fully polymerize the printed ceramic parts. The addition of zirconia and ceramic particles to the binder/resin material to formulate the suspension is challenging; it increases viscosity and interferes with the polymerization process due to the mismatch in the reactive indices between the monomer and the ceramic particles.[28,29] The

Fig 2 Full-coverage zirconia restoration fabricated using a DLP printer.

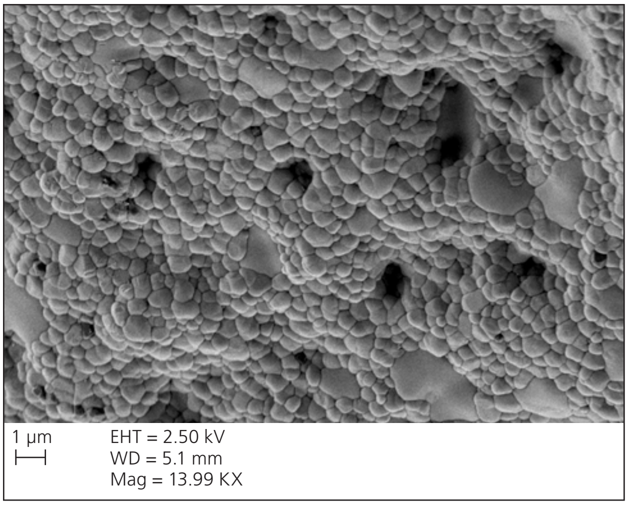

Fig 3 SEM image showing flaws/porosities within 3D-printed zirconia.

net result is a compromised printing process, relegating the quality of the printed parts to a level inferior to that required for clinical use. The available literature on the printing of ceramics and zirconia shows that inter- and intralayer porosities remain a challenge with all of the vat AM technologies (Fig 3). During the de-binding phase, a high temperature should be applied to decompensate and evaporate the polymeric binder. The temperature selected is highly influenced by the physical properties of the resin particles, including size and quantity. De-binding temperature and time are critical to avoid cracks within the final printed parts. Sintering is required to formulate the dense solid part via additional heat treatment with controlled time and temperature ramps.[28]

Osman et al[30] presented the first study in the dental field related to the fabrication of customized 3D-printed zirconia dental implants. In their experiment, the dimensional accuracy of printed zirconia implants, biaxial flexure strength, and surface roughness of printed zirconia disks were evaluated. The results showed high dimensional accuracy of the printed implants, with a root mean square error (RMSE) value of 100 µm, and high strength values of the printed disks, with a mean flexural strength of 1,006.6 MPa when printed at 0-degree build angle.

A recent systematic review revealed that though 3D-printing of zirconia is very promising, achieving high dimensional accuracy without structural porosities is challenging.[31] Efforts were made by Zhang et al[32] to print ceramic parts using the CLIP technique, which they suggested provides more isotropic mechanical properties mediated by the layerless AM technique. Thus, 3D printing of ceramics with optimal physical and mechanical properties remains an interesting topic for future investigation.[32]

POWDER FUSION

In the powder fusion technique, a heat source/high-power laser (Nd:YAG) is used to fuse, melt, or sinter powder particles of printable material. The selective laser-sintering (SLS) process was developed in 1989 and starts with a tank of polymeric/ceramic powder and a laser-focused beam that can trace the cross-section of the object and heat the powder particles just below melting temperature to join them.[33,34] Then, the build platform is lowered to the distance defined by the layer height, and the surface is recoated with another fresh layer of powder. The process continues until the object is complete. The unsintered powder remains in place to support the object during the building process.

SLS can be used with materials that are in powder form and can be melted and resolidified, including metal-based, ceramic-based, and polymeric-based powders. Metal-based SLS printing uses titanium and its alloys, as well as cobalt-chromium (Co-Cr) alloys, and is most commonly used for the fabrication of prosthetic metal frameworks.[35,36] Ceramic materials such as aluminum oxide and titanium oxide are mainly used for the fabrication of dental restorations and prostheses. In the polymeric category, polyether ether ketone (PEEK) is the most commonly used polymeric material in maxillofacial reconstructions for bone replacement.[37] Though printed parts with high accuracy can be fabricated with SLS, stresses and porosities can be inherited between the layers due to partial melting of the powder particles[38] (Fig 4).

Other powder fusion methods that can be used for printing metals are selective laser melting (SLM) or direct metal laser sintering (DMLS).[39] A carbon dioxide (CO_2) laser is used to melt metal powders. Low thermal

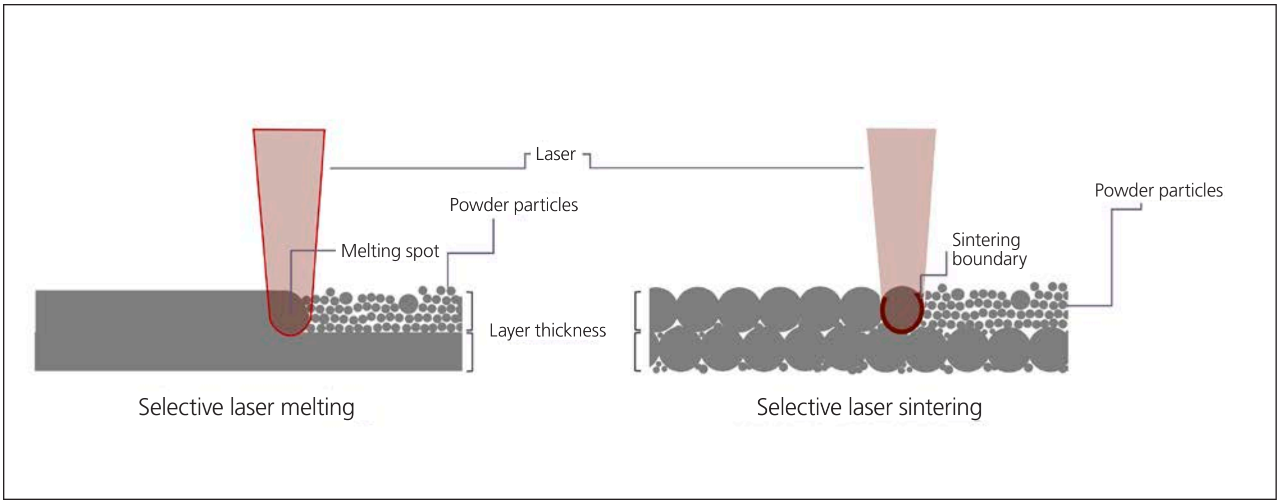

Fig 4 SLS and SLM. With SLM, the laser beam completely melts the powder particles, whereas in SLS, porosities and unsintered particles are present as the particles are fused rather than melted.

conductivity metals, such as stainless steel and titanium, result in better printing results and high accuracy of the printed parts. Unlike SLS, a support structure is necessary for SLM and DMLS, both to dissipate the heat and the stresses generated and to prevent distortion during building process. Similar to the post-processing step in the vat polymerization technique, heat treatment is necessary with SLM to eliminate the internal stresses caused by thermal gradients induced during fabrication.[40]

The accuracy of printed parts in powder fusion methods is dependent on laser spot size, layer height, and powder geometry. Despite the high cost of SLS, fixed prostheses can be successfully printed using SLS and SLM with comparable marginal fit to frameworks fabricated using conventional techniques, with accuracy values ranging between 75 and 99 μm.[41–44] Xiang et al[45] and Wu et al[46] showed that the bond strength between ceramics and parts fabricated with SLM are similar to the bond with parts fabricated with conventional cast techniques.

SLM is also useful for the fabrication of metallic removable partial denture (RPD) frameworks, with a high level of detail.[47] Bibb et al[35] used the SLM technique to fabricate RPD framework using stainless steel and Co-Cr alloys with fit and accuracy comparable to cast frameworks. Williams et al[48] showed acceptable fit of the SLM framework in a bilateral lower free-end saddle case.

AM PROCESS

Despite the differences in the working technique between various types of printers, the manufacturing process is similar for all the techniques. Figure 5 illustrates a summary of the steps involved in the manufacturing process. Four main phases can be identified: data acquisition, preprocessing, printing, and post-processing.

Data Acquisition

As in any CAD/CAM technique, the process starts with digital data acquisition.[7] Data can be acquired directly via intraoral scanners or indirectly by scanning a study model or an impression using tabletop scanners. Volumetric 3D data can be acquired directly from CBCT, with or without segmenting the area of interest.[49] Whether the model is ready for manufacturing or needs designing in a different software, the exported digital data must be readable by the 3D printer selected for the case. The most common format is standard tessellation (STL), which is compatible with most printers.

Preprocessing (Virtual Slicing)

Because AM-fabricated objects are produced layer by layer, the 3D digital file must be virtually sliced into 2D layers so that the computer/3D printer can trace the geometry of the object in each layer. Prior to fabrication, the digital file is subjected to preparatory steps to translate the information to the printer for fabrication. These steps are performed within the printer slicing software. The user selects the direction of the print by changing the orientation of the model within the build platform. This step is crucial and directly influences the physical and mechanical properties of the printed part.[50–53] Changing the build direction of the same layer thickness can affect the accuracy and surface roughness of the printed part.[54] The influence of build orientation on fracture resistance, mechanical properties, surface roughness, and dimensional accuracy has been heavily investigated. Orienting the object so that the layers are perpendicular to the

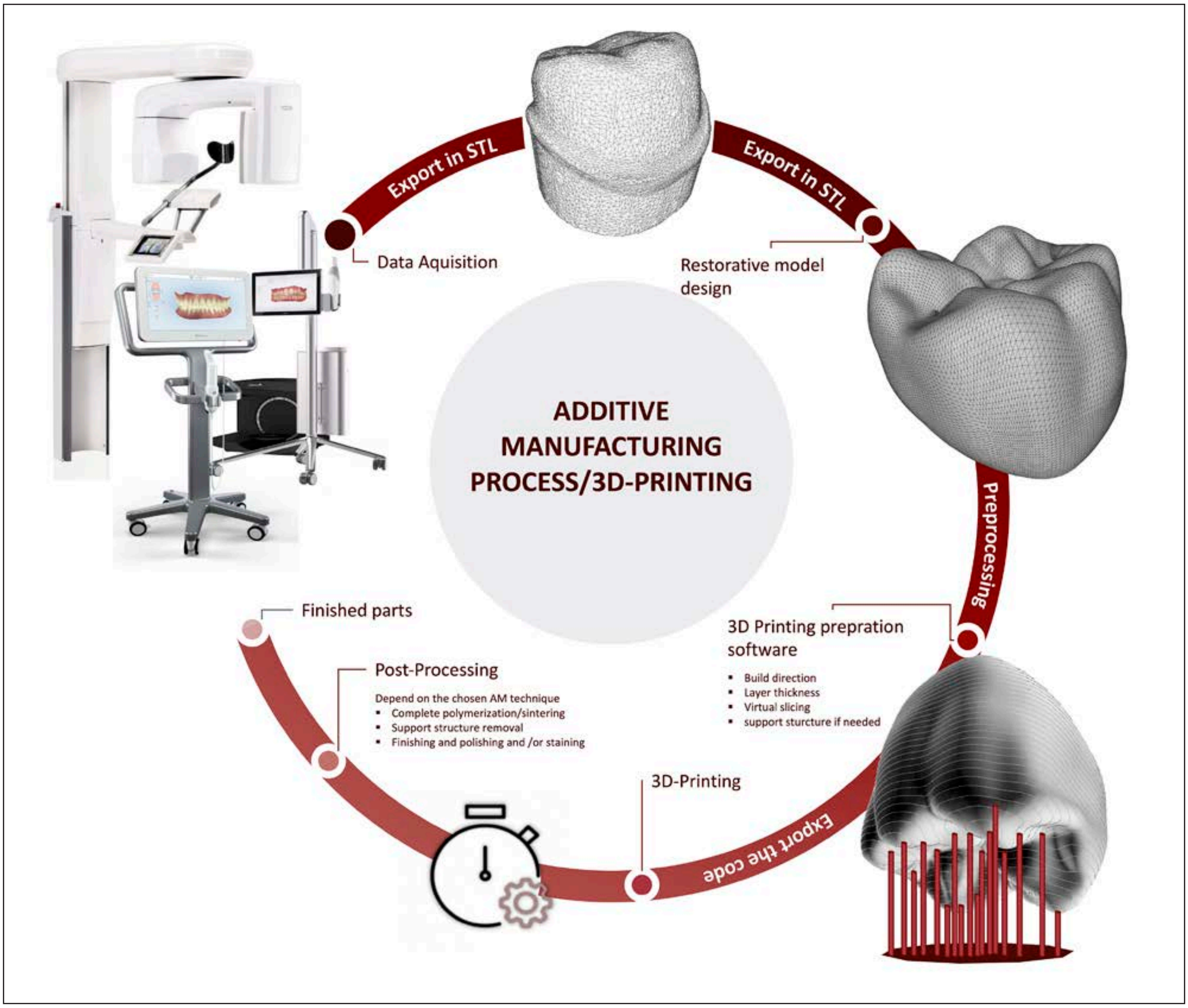

Fig 5 Flowchart showing the full process of AM technology.

applied load has been shown to improve the mechanical properties of the printed part.[52,55]

Depending on the selected AM technique, the object needs support structure to optimize the build process. In lithography-based printers, a support structure is mandatory to support surfaces that lack self-support.[17] In metal SLM printing, a support structure is needed to dissipate the heat generated during the fabrication process to melt the metal powder. Other forms of powder bed fusion do not need support structure because the unsintered powder can be used to support the model during printing.[7]

The influence of support structure dimension on the dimensional accuracy of full-coverage restorations has been previously investigated. Alharbi et al[17] found that a well-distributed, thin support structure results in higher dimensional accuracy of the printed parts. Further, with any selected build angle, care must be taken when placing the support structures to avoid interfering with the fitting surface of the prosthesis, nor should the support structure be placed close to critical structures, such as the restorative margin. Study models are frequently printed with a hollow internal volume/base design to reduce print time, weight, and cost. Lack of an internal support structure in the base of printed models has been shown to decrease the dimensional accuracy of the printed part.[56]

It must be emphasized that the build direction, layer thickness, and support structure are all interrelated and known to influence the accuracy and physical and mechanical properties of printed parts. In most cases, the build direction is selected based on a compromise in which some characteristics are improved at the expense of others.[50]

Printing

In this stage, the printer receives the instructions from the preparatory software so that the light/laser can trace the 2D section of the model and print each layer. The process continues layer by layer until the print job is completed. The print time is calculated from the start of the print job and can be monitored on the display screen to track the progress of the fabrication. After printing, the object is kept on the build platform, either so that the excess resin drips (in case of vat polymerization) or so the object cools (in case of SLS/SLM). Then, the model is removed from the build platform with caution and carried to the next phase for further processing.

Postprocessing

Post-processing procedures are needed with almost all printing technologies to attain the desired mechanical, physical, and esthetic properties of the printed part, as well to achieve the dimensional accuracy required for any part intended for clinical use.[57] With vat polymerization techniques, the post-processing step involves post-polymerization/sintering, support structure removal, and finishing and polishing procedures.[58] The printed part is washed in alcohol of a specific concentration as per manufacturer recommendations to remove the excess printing resin material. This is followed by insertion into a UV-curing unit to complete the polymerization of the part. Next, the support structure is removed manually, and finally, the printed part is finished and polished. These post-processing steps are essential and proven to influence the final quality of the printed part.[50]

Aati et al[59] showed that the physiomechanical properties of 3D-printed denture base materials can be improved by increasing the post-curing time up to 20 minutes, resulting in comparable performance to conventionally heat-cured base resin material. Similarly, Alkhateeb[60] showed that the fracture strength increases as the post-curing time increases.

With a powder bed fusion technique, post-processing is required to remove the excess powder material. Following the removal of excess powder, airborne particle abrasion and polishing are performed to improve the surface quality of the printed part. Specific to the powder fusion technique, thermal treatment is often required to remove the residual stresses and improve the mechanical properties of the printed object.

CONCLUSIONS AND FUTURE PROSPECTS

This review provided an overview of the AM techniques used in dentistry, providing readers with a road map for selecting the appropriate technology for a given application (Fig 6). When choosing the technology, one should consider the intended outcome, accuracy, speed, cost, surface finish, and the range of materials available.[7] SLA technology permits the highest degree of dimensional accuracy and superior surface quality, whereas DLP and LCD technologies offer a cheaper and a faster alternative that can be very applicable for printing diagnostic study models. Though the initial cost of 3D printing might be high, the whole manufacturing market is shifting from mass to custom, on-demand production, which requires more flexibility in the tools of the production process. This was clearly reflected during the 2020 pandemic period, when in-house production was the most common fabrication method applied. Further, AM plays a very important role in customization and the freedom of design and fabrication of complex parts.[61]

The AM process starts with acquiring the STL file and continues until completion of post-processing the parts.[62] Build orientation and layer thickness are interrelated, and their influence on the printed parts has been extensively studied in the literature.[17,18,54,63–67] During AM, no absolute single orientation is recommended. Rather, it must be a conscious exercise to examine the effects of a particular print orientation/direction on a printed part and the intended clinical use of that part.

Prudence is required when comparing the data available in the literature on different AM technologies, materials, and printing parameters, especially when considering the growing scientific research on these topics. Lack of consistency in relevant data published between 2016 and 2023 on the definition of the build angle makes interpretation of the results critical. Further, there is a need for randomized clinical studies to evaluate the available 3D-printed restorative materials on the market, as the available clinical evidence is limited to case reports and dental techniques.[68,69]

Continuous development in AM technology and the wide range of printing materials being introduced is sure to expand the integration of 3D-printing techniques within dentistry. Until recently, printing of single-shade dental restorations was considered a drawback of the vat photopolymerization technique. The leap in the development of printers and materials has now resulted in the emergence of new, multi-color resin material for the fabrication of multi-shade dental restorations. Further research is needed to improve current restorative materials, including ceramics and zirconia, as well as biocompatible silicone materials for maxillofacial prostheses.[70]

Ongoing research is being performed to develop novel techniques for fabricating layerless objects. A new, evolving printing technology operates in a manner similar to the principles behind CT. It is referred to as the *tomographic projection technique* and is suggested to eliminate the interface between the layers in printed object.[71] In this technology, the light source radiates into a rotating container of photopolymerizable resin material. The object is then built by superimposition of 2D projection that propagates through transparent resin.[71]

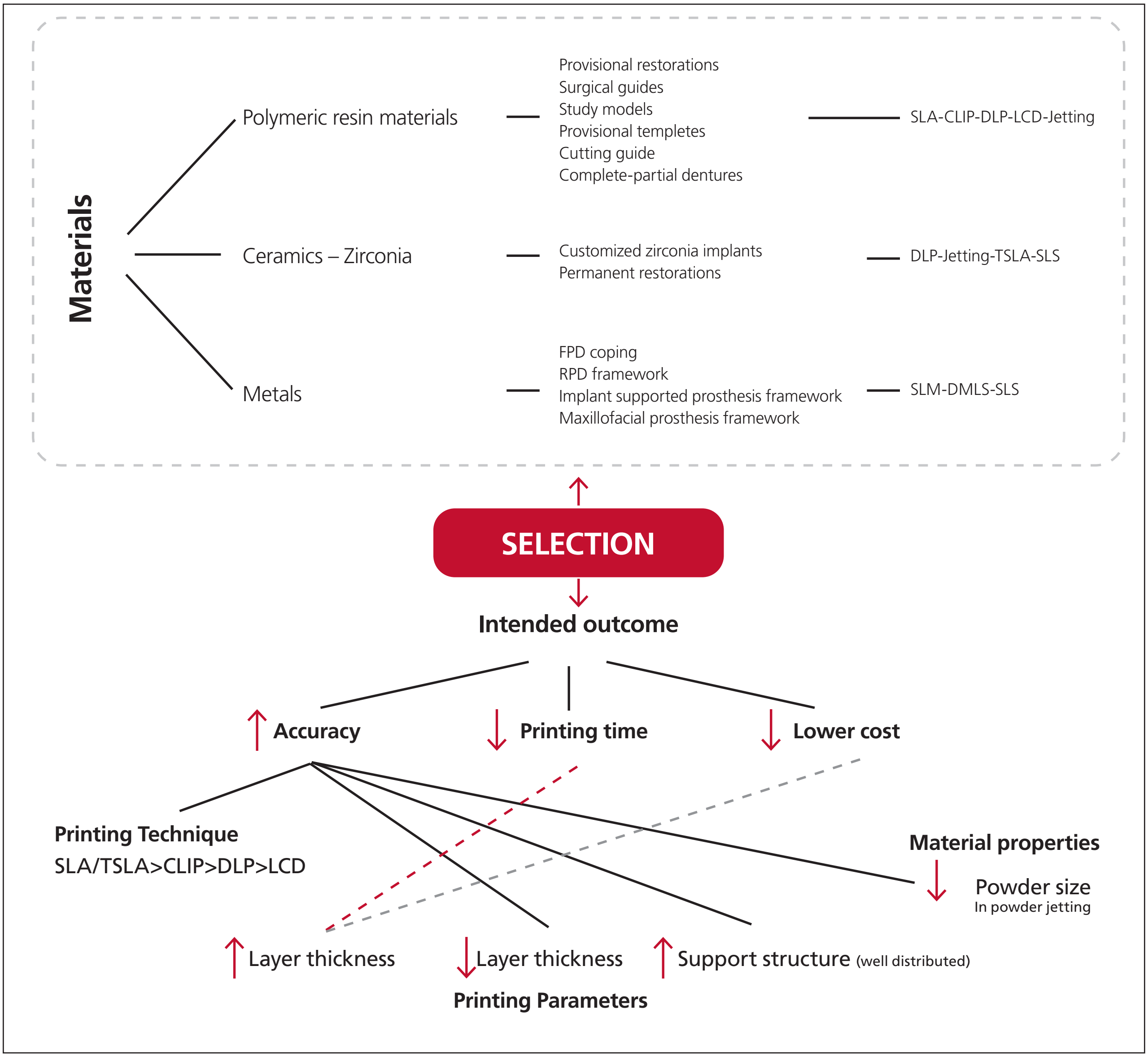

Fig 6 Decision tree for selecting the appropriate AM technique based on the selected material or the intended outcome of the production.

Using AM to fabricate a dental model, a precise dental restoration, or a conceptual model is far more than just a simple fabrication process. It is a beacon of creativity and freedom in the design of customized treatment solutions with a digital workflow. Clinicians should have a basic knowledge of the principles behind each technology, as well as the associated fabrication parameters. Each 3D printer behaves a little differently, even within each technique, and so does each type of material on each machine.

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