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Literature Review

3D Printing Part 1: A History and Literature Review Of 3D Printing Technologies Used In Dentistry

Adam Nulty [1*]

[1] University of Leeds, Woodhouse Lane, Leeds, LS2 9JT; dnabn@leeds.ac.uk
* Correspondence: dnabn@leeds.ac.uk

Abstract: Introduction: The term 3D printing is commonly used to depict an assembling method whereby the final form of an object is the result of the addition of different layers to build the frame of an object. This procedure is more accurately portrayed as additive manufacturing and is likewise alluded to as fast prototyping. The term 3D printing, in any case, is generally new and has been an active part of current developments in Dentistry. Much publicity encompasses the evolution of 3D printing, which is hailed as an innovation that will perpetually change CAM manufacturing, including in the dental sector. This review is the first part in a 3D Printing series that looks at the history of 3D Printing, the technologies available and reviews the literature relating to the accuracy of these technologies. Conclusions: The recent advancement in digital dentistry to incorporate these tools has modernised dental practices by paving the way for computer-aided design (CAD) technology and rapid prototyping. The use of 3D printing has led to 3D digital models produced with intraoral scanners (IOS), which can be manipulated easily for diagnosis, treatment planning, mockups, and a multitude of other uses. Combining 3D Printing with a 3D intraoral scan eliminates the need for physical storage but makes it to retrieve a 3D models for use within all dental modalities.

Keywords: 3D printing, intraoral scanners, digital dentistry, trueness, precision, accuracy, history

1. Introduction - The History Of 3D Printing Technologies

The term 3D printing is commonly used to depict an assembling method whereby the final form of an object is the result of the addition of different layers to build the frame of an object. This procedure is more accurately portrayed as additive manufacturing and is likewise alluded to as fast prototyping. The term 3D printing, in any case, is relatively new and has been an active part of modern developments in Dentistry.[1] A great deal of publicity encompasses the evolution of 3D printing, which is hailed as an innovation that will perpetually change CAM manufacturing, notably within the dental sector.

The utilisation of 3D printing that requires sub-millimetre precision has drawn the consideration of authorities in medicine, who began to develop the process in the 1990s. However, the inception of 3D printing began in the 1980s. In 1983, Charles Hull printed, for the first time, a three-dimensional

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object using stereolithography.[2] Since then, 3D printing has become ever more integral to the pro-

duction workflows of dental laboratories and now dental surgeries, in a chair-side setting, augmenting possible workflows using the digital technology available with CAD/CAM machinery.

Figure 1. An Example of A 3D Printer Used in Dentistry, the IDDA 3D Printer

In prosthetic design, for example, modernised 3D printing now allows not only prototyping but the production of final parts and frameworks with flexural strengths of 80 MPa and higher.[2] The CAD/CAM applications used in Dentistry have, in turn, followed the advancement of 3D printed parts. Oberoi et al. [3] stated that the motivation behind headway in 3D printing for medicine and dentistry leads from the production of small-scale creations that facilitate the sharing of patient information and the creation of planning tools to better patient care. This pattern is reflected by the expanding number of discussions on this subject of 3D printing.

2. Relationship with Utilisation of Intraoral Scanners

The increased utilisation of intraoral scanners has lead to dentists looking to 3D printing to make a physical model of the scanned dentition. Although it may not be necessary to 3D print a model in every case, the 3D printed model might be many parts of the planning and manufacturing processes involved with dental treatments. Including, for example, a model portraying the eventual outcome of treatment from a digital mockup using tooth libraries. Dawood et al. [1] stated that some examples of the uses of 3D printing include the production of drill guides for dental implants, the production of physical models for prosthodontics, orthodontics, and surgery, the manufacture of dental, cranio-maxillofacial, and orthopaedic implants, and the fabrication of copings and frameworks for implant and dental restorations.

The use of orthodontic clear aligners to align patient's teeth is now vastly easier because of the development of 3D printed models for the production of said aligners. As orthodontic alignment occurs over a period of months or years, many aligners are required. The fast prototyping of models lends itself to this as several models in the orthodontic sequence can be printed easily and quickly.

Many users have utilised 3D printing innovations to make novel dental creations with a permeable or detailed surface. 3D printing can deliver complex geometries, for example, a bone-like morphology, which may not be created by processing alone to aid in treatments such as implant planning and guided implant surgery.

In a study by Brown et al., [4], rapid prototyping was used to transition a traditional clinical workflow to a fully digital workflow. The accuracy of the conversion from digital impressions to 3D printed models was compared to alginate to poured stone casts. The study found that 3d printing produced clinically acceptable models, and the fully digital workflow should be considered an entirely viable option for dental clinics.

Dental laboratory facilities can now create crowns, bridges, stone models, and various orthodontic appliances using techniques that take patient data in the form of a 3D intraoral scan then use 3D printing and CAD/CAM to prototype or manufacture the eventual prosthesis. Kim et al. [29], discussed that 3D printing has been used for the production of models for quite some time, and is now becoming more ubiquitous in the production of restorative and implant guides and prostheses themselves. Computerised innovation and 3D printing have fundamentally changed the involvement of the dental lab within restorative and implant dentistry resulting in a greater refinement in the production capability and overall accuracy.

Use in Education

Along with increased involvement in both the chairside and laboratory setting, Oberoi et al.[3] looked at there being a much-increased number of research projects and studies involving 3D dentistry. Through this increased number of studies, 3D printing is looked at more favourably, and therefore consumer confidence has also grown. 3D printing and the research setting have also lead to the inclusion of this technology in the education setting, both postgraduate with academies such as the International Digital Dental Academy, and in a growing number of undergraduate Universities to help prepare and advance the abilities of trainees and students. Through a combined approach of research, training in dentistry, and clinical treatment, it is conceivable that 3D printing and fast prototyping can provide a plethora of alternate scenarios for education where alternative scenarios can be looked at with characteristics such as porosity, design, and surface texture changed quickly and easily. [5]

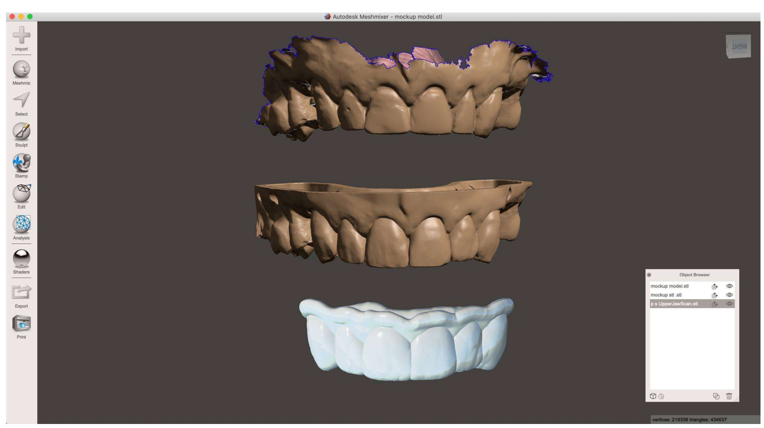
Use in Orthodontics

Through the evolution of digital dentistry, what was once a complex and tedious procedure has now become simple, effective, and easily planned both via the laboratory and also chairside. 3D printing has also allowed the orthodontic procedures to be quicker to adapt to changes in treatment requirements over the conventional workflow process as new intraoral scans can be incorporated to amend/refocus alignment at any stage.[6,7] By incorporating digital dentistry element, the orthodontist can drastically quicken treatment time while also minimising storage space and material waste. The future of 3D printing and orthodontics ultimately lends itself naturally to the direct 3D printing of orthodontic clear aligners. This development will be more efficient and less wasteful but will rely on the development of elastomeric resins that retain shape after deforming. Mahamood, Khader & Ali [7] concluded that with a 3-D printer doing the diligent work, dental labs can remove the manual workflow through the use of 3D printing to further develop their business. Conventionally, the majority of orthodontics heavily relied on using alginate as an impression material in dentistry. These replicas are used for plaster models to fabricate structural orthodontic oral structures including, mouth guards, retainers, expanders, and space maintenance devices. However, the advancement in the digital manufacturing technologies have allowed the use of 3D printing in fabricating dental and orthodontic appliances from 3D model designs.[8,9]

Figure 2. An Example of Direct-3D printed Aligners printed from STLs using an Asiga Max UV DLP 3D Printer and an experimental resin.

Use in CAD/CAM Dentistry

When manufacturing parts or objects required during treatment, one can utilise either subtractive or additive manufacturing techniques. Subtractive manufacturing is generally more common. The process requires a block of material before the virtual shape of the objective part or object is carved, ground, or milled by evacuating material from the material to leave the final 3D object. This technique can be utilised in the chair side setting to create veneers, inlays, crowns, and bridges by depending on Computer-Aided Design (CAD) or Computer-Aided Manufacturing (CAM) software. The virtual 3D CAD design of the restoration is then converted to instructions to direct and drive the CNC milling machine to shape the part in an inherently destructive and wasteful process. While machining smaller parts is common for dental laboratories and some chair side clinics, it would be impractical for these settings to machine larger full arch models via a subtractive process. Thus subtractive engineering and manufacturing have limitations, and these larger models have historically



remained within the analogue/manual production of mould stone casting.

Figure 3. An Example of a CAD restorative Mockup and a direct 3D printed stent based on the mockup printed in a flexible clear resin.

3D printing, otherwise called additive manufacturing (AM), fast prototyping, layered assembling, or strong freestyle creation. Jain, Supriya, & Gupta[8], described the manufacturing procedure where layers of material are laid continuously under programmed control to make a three-dimensional item. The protocol of this manufacturing strategy is that the virtual 3D structure is "sliced" into layers of a set thickness. The 3D printer then produces each layer one at a time to form the overall geometric structure. [9]

The upsides of additive manufacturing over subtractive include; more efficient utilisation of the material with little waste, the capacity to dispose of specific manual procedures, adaptability of the machine to reproduce complex object geometry, intricacy, and an assortment of materials available. As promising as additive manufacturing is, and despite the incredible speed of progression, there are a few limitations at present. However, just as 3D printing hardware and materials have historically been expensive and are now being produced at highly competitive prices, these limitations will most likely be overcome and overcome quickly. The current limitations include the appearance of the final object because of the layering of the material and the long-term strength of biocompatible materials, which requires further development and study. In any case, additive manufacturing has been an extraordinary development in contrast to subtractive manufacturing, with access to newer 3D printing hardware ever- evolving and growing in features, accuracy, and speed.

Overall three-dimensional design, viewing, and CAD/CAM have had a significant effect on the advancement in all areas of dentistry, with 3D printing playing a central role in current developments. With the assistance of intra-oral 3D scanners, it is conceivable to use 3D printing to make precise, accurate, and complex geometrical structures with a wide assortment of materials.

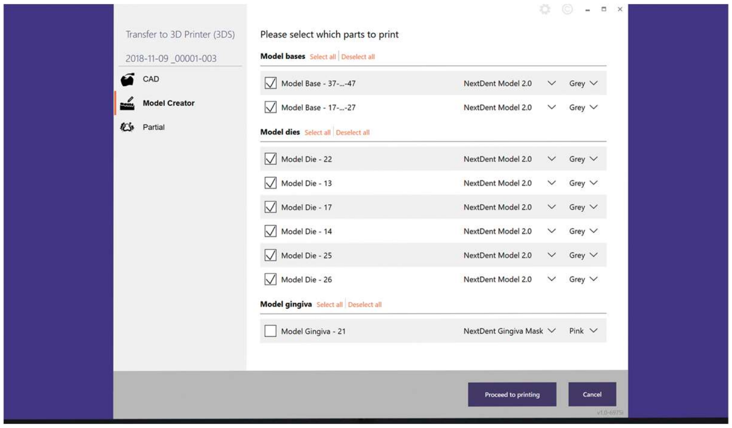


Figure 4. ExoCAD and other CAD software directly integrating the 3D Printing slicer software.

Today, AM has been considered a breakthrough technology that represents the fourth industrial revolution by transforming the production processes of manufacturing objects. The conventional manufacturing methods involved several steps of converting raw materials to a fully finished, assembled, and usable end-product [10]. In addition to time-consuming, conventional manufacturing technologies are associated with high production costs, high energy consumptions, and lack flexibility of end-product design.

Improved Production Efficiency

However, the 3D printing technologies are a paradigm shift that eliminates the complex processes in conventional manufacturing by reducing energy consumption and cost of production, respectively.[11,12]

AM is characterised by increased capacity to manufacture a wide range of functional products on market demand more easily due to increased design flexibility. In addition, the manufacturing processes are cost-effective, with reduced waste and blend unique materials needed to improve the performance of the end-product and extend its durability.[11]

The technologies used in AM have found several industrial applications such as healthcare, aerospace, automotive, and consumer electronic devices.[9] In the healthcare sector, the potential of 3D printing technology to fabricate customized patient-specific implants with needed precision and accuracy has increasingly being employed in different healthcare specialties, including orthopedic, cardiology, and dentistry. Some examples of 3D printing technologies in healthcare include implantable bones, rib cages, and heart valves.[3,12]

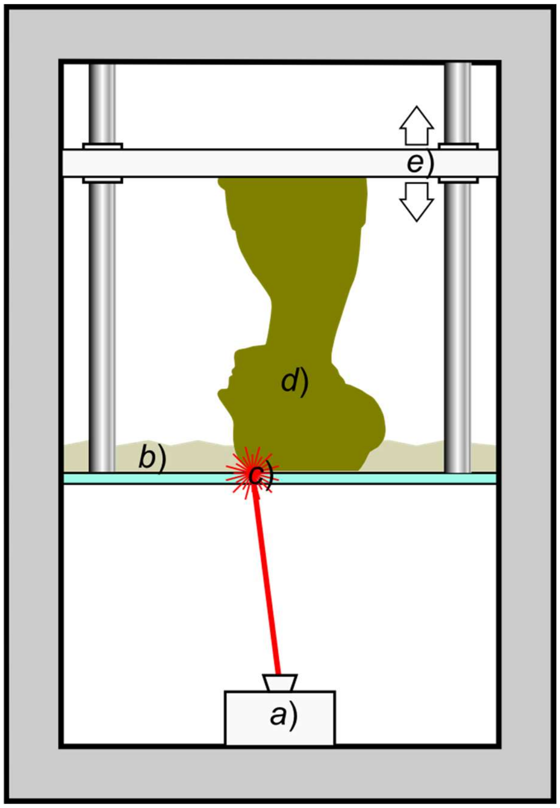
A number of diverse materials such as metals, ceramics, and polymers have been processed to fabricate numerous implants using 3D printing.[13] In the context of dentistry, the applications of 3D printing technologies involve maxillofacial implants, dentures, and other prosthetic aids. It has been shown that 3D printing technologies can easily create anatomical models for surgical training, diagnostic planning, and orthodontic setups in various areas of dentistry.[14]

3. Types of Technology

Today, there are several different 3D printers available in the market for applications in dentistry. The primary 3D printing technologies adopted include stereolithography, photopolymer jetting, and digital light processing that uses light to cure resin.[3]

i) Stereolithography (SLA)

Stereolithography (SLA) is the most popular and oldest 3D printing technology, which comprises a vat of photosensitive resin as a platform for the model-building, and an ultraviolet laser to cure the resin. The SLA uses a high-powered laser to convert the photosensitive liquid resin contained in the reservoir into the desired 3D solid-shaped plastics in a layer-by-layer fashion using a low-power



laser through the process known as photopolymerisation.[15]

Figure 5. Schematic representation of Stereolithography: a light-emitting device *a)* (a laser or DLP) selectively illuminates the transparent bottom *c)* of a tank *b)* filled with a liquid photo-polymerising resin. The solidified resin *d)* is progressively dragged up by a lifting platform *e)[44]*

In SLA, two motors known as galvanometers, controlling the X and Y axis respectively, work together to angle a pair of mirrors to aim a laser beam across the print area in the resin vat, thus solidifying the resin. The layers of the 3d object are built following a particular direction to cure a photosensitive vat containing the resin based on the CAD design [5]. After each layer is cured, the build platform is raised to allow resin to flow into the area cured and then lowered by moving back along the z-direction to allow the second layer to be cured. The process is repeated consistently until a 3D product is wholly fabricated.[3]

The underlying technology used in SLA has primarily remained the same for years. Nevertheless, the recent technological advancements have led to the next generation of 3D printers, which are smaller, relatively inexpensive, and more efficient compared to the traditional SLA technique.[15] The SLA 3D printing technologies also come with several advantages, including reduction of resin volume and elimination of an oxygen inhibition layer on the surface, which consequently minimises the total amount of porosity trapped in the final product. The SLA technique has also been shown to offer high manufacturing accuracy along the x-y axis.[17] Using the z-direction, the accuracy of SLA technique in 3D printing technology is more important as it depends on multiple factors [19]. These factors include CAD design, layer thickness, material properties [16], data processing, post-processing/slicing procedures [16], and building orientation of the virtual model, particularly in curved or angled surfaces.[18]

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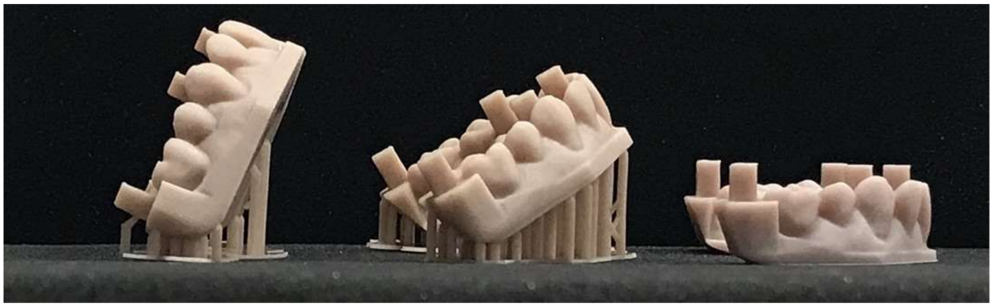
The entire fabrication process of SLA technique involves three different phases. The preparatory phase involves selecting the build orientation, slicing the STL file, and generating the support structure. The actual build is enhanced in the second phase, whereas the third phase encompasses removal of the support structure and then post-curing of the fabricated structure.[19] In these phases, the build parameters are commonly interrelated and have been reported to have a significant influence on mechanical properties and dimensional accuracy of the complete fabricated structure.[20] Additionally, the total build and finishing are also dependent on the build parameters set.[21] A study by Alharbi, Osman, and Wismeijer [16] examined the effect of build angle, and support configuration (thick versus thin support) on the dimensional accuracy of 3D printed full-coverage dental restorations. In this study, the root mean square estimate value and colour map results suggested that the build angle and support structure configuration had a significant influence on the dimensional accuracy of 3D printed crown restorations. It was concluded that the selection of build angle should offer the crown the highest dimensional accuracy and self-supported geometry. As a result, this allows for the smallest necessary support surface area and reduces the time needed for finishing and polishing.[17]



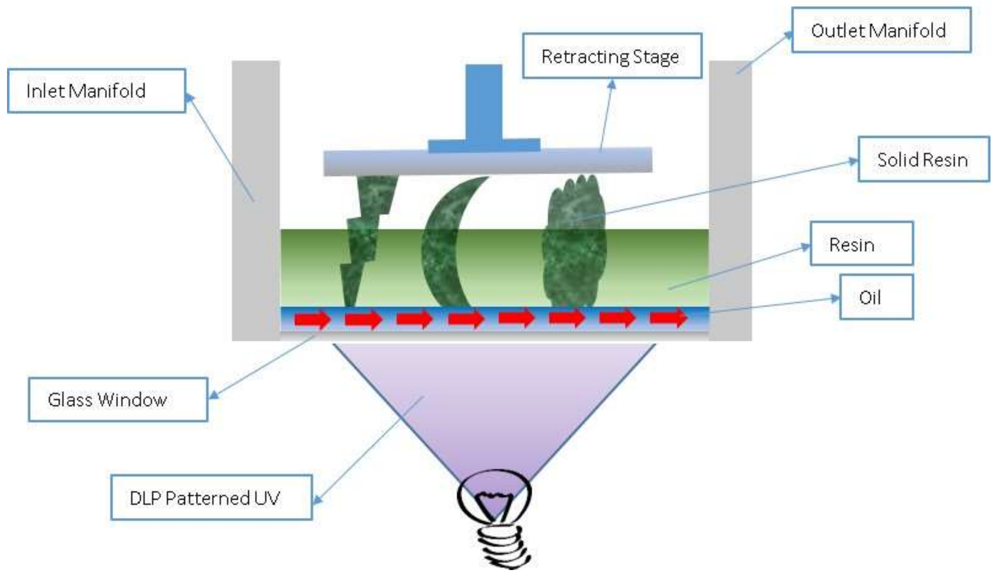
Print Effect and Direction of Object

Figure 6. A study by Brenes, Renne et al considered the impact of print layout and direction but found that the effect was specific to each printer type and resin used.[45]

In another study examining whether build direction affected the mechanical properties of 3D printed complete coverage interim dental restorations, it was reported that materials printed vertically (90o) had higher compressive strength than those printed horizontally (0o) [17]. A recent study by Alharbi, van de Veen, Wismeijer, and Osman [19] found that the built angle or layer orientation influenced the flexure strength of the hybrid resin material printed using SLA technique. It was reported that the vertically printed specimens had a significantly lower mean flexure strength of 88.2 MPa compared to 90.5 MPa of those printed horizontally.[19]

ii) DLP Technologies

In addition to SLA, other 3D technologies that use light to cure the resin include the digital light processing (DLP), as well as photopolymer jetting, also known as polyjet or inkjet-based system. Both polyjet or photopolymer jetting, and DLP techniques embrace the use of AM technologies to fabricate a layer-by-layer 3D model based on the digital models (Al-Imam et al., 2018). However,



the 3D printing technologies used in polyjet and DLP differs from those used in SLA technique.

Figure 7. Schematic representation of DLP 3D Printing technology. The light is patterned through a projector or LCD to cure the resin layer before the retracting build platform peels and moves up before returning to cure the next layer.

Typically, DLP uses a conventional light source such as a liquid crystal display panel, arc lamp, or projection source to cure the surface layer of a vat with photopolymerising resin in a specific direction based on the digital model. The use of light to cure resin is a significant similarity that characterises both the SLA and DLP 3D printing techniques.[5] However, the 3D printing technologies used in DLP involves the use of a projector screen or arc lamp as the source of light rather than using a laser as in the case of SLA technique.[22] Using a digital projector screen, the DLP flashes a single image of each layer in square pixels across the entire platform where the resolution of DLP 3D printer corresponds to the pixel size. In contrast, the SLA technique produces laser spot size images with lower resolution; thus, representing DLP technique as an alternative advancement in the SLA 3D printing process.[3,22]

iii) Laser Sintering and Polyjet

In the context of the polyjet 3D printing technique, a moving piston is used to dispense a known amount of raw powdered-form material, through which a roller is consequently used to distribute and compress the powder at the top of the fabrication chamber. The multi-channel jetting head then drains a liquid adhesive material in a 2D pattern on the powder, allowing it to bond and create a layer of the object.[23] Once a layer has been formed completely, the piston helps spread and join the powder to the next layer. As a result, the continuous layer-by-layer method progressively achieves a complete built-up of a prototype. However, the unbound powder is subsequently swept up into a heating process, leaving the object's fabricated part strong and complete.[24] The main similarity between the SLA and polyjet 3D printing technologies is based on the fact that they use ultraviolet light to cure the photosensitive polymer resin by building it into successful layers. In both techniques, the initial layer of resin is cured onto a build platform where each subsequent layer is directly cured to the previous layer of the cured resin in the Z-axis to create a 3-D object.[3] Nevertheless, the photopolymer jetting differs from the SLA technique. It does not use a light-sensitive laser to cure a vat of photopolymer resin by building it to a successful layer. Instead, the photopolymer jetting or polyjet printing utilises an ink type print-head jets to spray the polymerised resin into the desired print areas where ultraviolet light source cures each spayed layer as it passes through.[5]

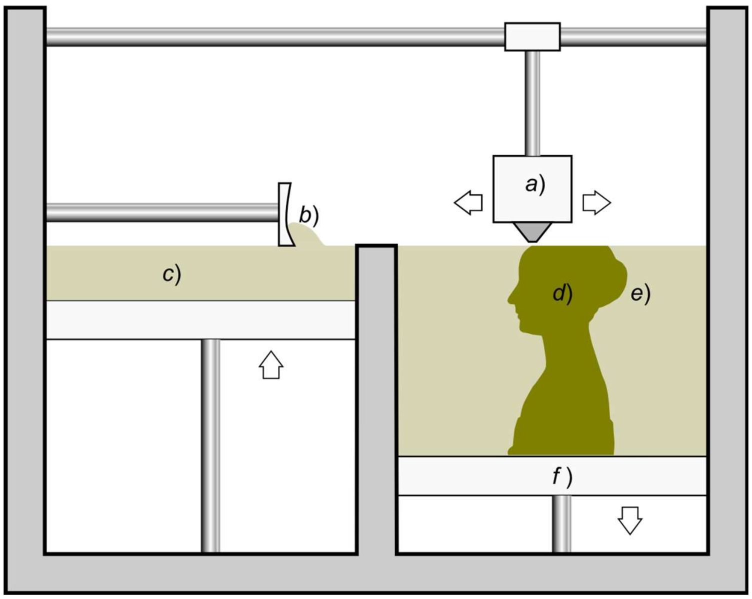


Figure 8. Schematic representation of the 3D printing technique known as granular binding; a moving head *a)* selectively binds (by dropping glue or by laser sintering) the surface of a powder bed *e)*; a moving platform *f)* progressively lowers the bed and the solidified object *d)* rests inside the unbound powder. New powder is continuously added to the bed from a powder reservoir *c)* by means of a levelling mechanism *b)*.

3D printing technologies have also led to the adoption of several techniques, such as selective laser sintering (SLS) and fused deposition modelling (FDM). In the SLS and electronic beam melting technologies, the powder is sintered in a heated chamber to a point below its melting point, where the scanning laser is subsequently used to build the 3D object.[5] The SLS technique uses a computer-controlled laser to fuse layers of particular powder material into a 3D model. The powdered material is distributed over the surface of a build cylinder by a roller, in which the powdered material is spread layer-by-layer on the top of the previous hardened layer and sintered repeatedly.[24] A laser beam is then directed to the surface of the firmly compressed layer of powder to bond all the parts of the 3D model layer-by-layer.[25] SLS technique has numerous advantages in dentistry as different thermoplastic materials such as casting wax, nylon composite, ceramics, and metallic materials can be used in different areas of prosthodontics.[25] Although SLS can be used to fabricate objects from metals and polymers, the technique is not only expensive due to its high capital expenditure (capex) and maintenance costs but also poses health risks associated with accidental explosion and dust inhalation.[5]

iv) FDM

For the fused deposition modelling (FDM), a nozzle releases small beads of thermoplastic material to construct a 3D model. Most of the 3D printers adopting the FDM technique are highly penetrated at the domestic level; hence, often referred to as 'home printers'. [1]The FDM is a fast prototyping technique that ejects a thermostatic material layer-by-layer from a nozzle controlled by temperature. In FDM technique, a filament of the thermoplastic material feeds into the temperature-controlled

FDM expulsion dome, which is subsequently heated to a free-flowing semi-liquid form. The head of the nozzle then directs the material into a place with adequate precision where it is solidified layer-by-layer within 0.1s. After the ejected material from the nozzle bonds to the layer below, the supporting structures of the object are then artificially derived by cutting them out from the 3D object model design.[24]

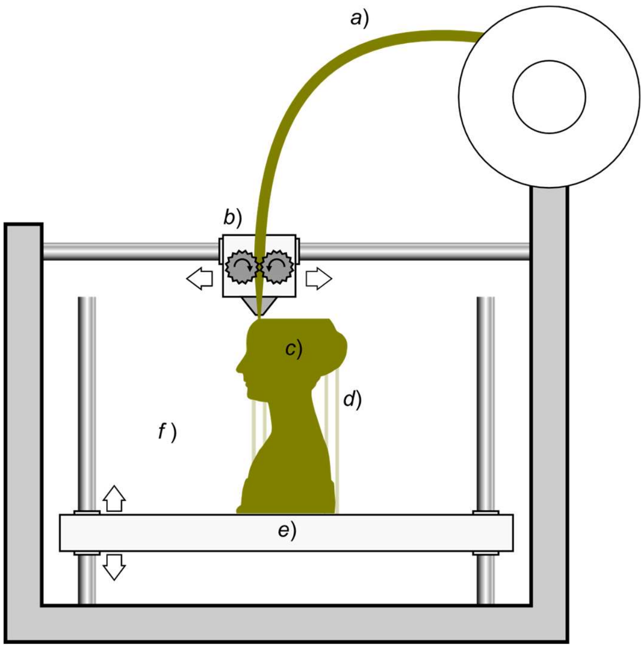


Figure 9. Schematic representation of the 3D printing technique known as Fused Filament Fabrication; a filament **a)** of plastic material is feeded through a heated moving head **b)** that melts and extrudes it depositing it, layer after layer, in the desired shape **c)**. A moving platform **e)** lowers after each layer is deposited. For this kind of technology additional vertical support structures **d)** are needed to sustain overhanging parts.[44]

4. Review on Accuracy

Dental prostheses manufactured using 3D printing technologies have been shown to have an acceptable degree of accuracy and precision compared to prostheses made using conventional models.[25] Evidence presented in the studies indicates that the accuracy of 3D printed models in dental casts can be useful in various areas of dentistry, including planning for diagnosis and surgical treatments.[26] In a study by Dietrich, Ender, Baumgartner, and Mehl [27] assessed the accuracy (trueness and precision) of two different rapid prototyping techniques by comparing the physical reproduction of 3-dimensional digital orthodontist resin casts using SLA and PolyJet system. This study indicated higher trueness in PolyJet replicas than the SLA models, in which the precision measurements favoured the SLA techniques. However, the study observed both replicas having a maximum of 127µm in dimensional errors [27], which was far below the recommended range between 300 µm and 500 µm for accuracy in orthodontic tests.[28] The study found that polyvinyl siloxane materials provided more accurate inter-occlusal recordings for a successful articulation of digital models compared to other materials such as Regisil Rigid, Futar Scan, Byte Right, and Aluwax.

A study by Kim et al. [29] explored the precision and trueness of dental models by assessing the differences in dimensions between the 3D printed models (fused filament fabrication (FFF), SLA, DLP, and PolyJet techniques) versus digital reference models. The 'trueness' was defined as the proximity of a model to a true value, in which the least accurate 3D printing model produced replica

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casts within 260 μm of the reference models, which was still below the reported guidelines. According to the study results, the 3D printing technologies had significant differences in the precision of all measurements, including the trueness in arch and tooth measurements. The results found that both the PolyJet and DLP techniques had a higher precision compared to FFF and SLA techniques, with the highest precision associated with the PolyJet technique.[29]

Several studies have also documented that both DLP and polyjet are 3D printing technologies that provide excellent accuracy and surface finish in dentistry.[3,11,30] However, a number of previous studies have shown that polyjet printing model produces more accurate models than any other 3D printing models.[27,31,32,33]

A study by Flügge et al. [34] assessed the accuracy of an intraoral digital dental scanner under clinical conditions, in which the results suggested that intraoral conditions such as saliva and limited spacing significantly affected the accuracy. Given that DLP and polyjet printers are two 3D printing techniques commonly used in dentistry, Brown et al. [4] carried out a study to assess their accuracy from digital intraoral impressions. The 3D printed models were produced from the digital impressions acquired directly from the oral environment and then compared with the stone models. Tooth measurements included mesio-distal (crown width) and incisal/occlusal-gingival (crown height), whereas arch measurements involved arch depth, as well as inter-canine and inter-molar widths. The significance of this comparison aimed at evaluating the accuracy of the entire digital workflow in a clinical environment where variables are not controlled, such as tongue, saliva, cheeks, lips, or movement. As stated in the previous studies, the findings indicated that both the DLP and polyjet printers produced clinically acceptable 3D printing models; hence, they should be considered as feasible options for clinical applications in orthodontic practice.[4]

3D Printed Models

In the recent past, the advancement of 3D printing in dentistry has been associated with increased accuracy of printed dental casts. Orthodontics continues to have a clear direct-printed model of a retainer that is not only clear, reproducible but also aesthetic.[3] Although the orthodontics relied on the use of alginate impressions of dental materials in dentistry, the digital scans of the patients' dentition can be used to directly fabricate oral appliances such as a retainer even without the use of a physical dental model. In 2014, a selective laser sintering (SLS) 3D printer was successfully used to fabricate a retainer directly from a digital model of cone-beam computed tomography (CBCT) without a physical model, as reported by Nasef, El-Beialy, and Mostafa.[35] Although the accuracy of fabricated retainer appliances was not assessed, the 3D printing technologies using CBCT provided simplicity, accuracy, speed, and patient satisfaction. The study results indicated 3D virtual retainer with user-friendly software seemed to be a promising technique that would eventually change the practices in present-day dentistry. It would pave the way for designing and manufac-

turing custom orthodontic appliances, which matches with the new digital orthodontic era.[35]

Figure 10. The IDDA Scan Method Training Model as given to the members of the International Digital Dental Academy to help with learning to use a 3D scanner. The STL file can be 3D printed.

A recent study compared the accuracy between orthodontic 3D printed and thermoformed retainers, in which 3D printed retainers were reported as more accurate and reliable than the conventional vacuum formed retainer[35]. Based on this study, it is important to note that CBCT was used to create the digital file to fabricate the two retainers. Furthermore, the two retainers were compared based on the linear measurements conducted manually using the digital callipers[35]. However, previous studies have shown that calliper measurements generated from iTero dental 3D model scanners are slightly more accurate than those produced from intraoral digital images in CBCT scans that do not account for gingival tissue.[36]

A recent study evaluated the accuracy of 3D retainers compared with the conventional vacuum-formed retainers and commercially available vacuum-formed retainers. [37] The results from this study showed that traditional vacuum-formed retainers had the least deviation from the original reference models (0.10-0.20 mm), followed by commercially- formed retainers (0.10-0.30 mm), whereas the most significant deviation (0.10-0.40 mm) was found in 3D printed retainers.[37] According to this study, all three retainers provided measurements within the 0.50 mm, which have been previously considered clinically acceptable for the assessment of digital articulation.[27]

A dental impression is a routine procedure for diagnostic and treatment planning, including the fabrication of dental prosthesis. In orthodontic practice, the dental impression should be practical, accurate, predictable, and easy to implement. The conventional impression techniques involving the use of paste-like material such as alginate (ALG) or polyvinyl siloxane (PVS) are often linked to limitations such as patient discomfort, ongoing high costs, requirements for well-fitting trays, and the need for pouring with dental stones.[38] Additionally, the quality of conventional impressions depends on materials' handling; that is, the distortion of the impression, stone material, and casting images of all intraoral problems.[39]

The advancement of digital technologies in the recent past has fostered digital work flow by increasing the potential of dentistry in producing dental prostheses. A major step of the digital workflow has been digital impressions with an intraoral scanner (IOS) according to the captured images of arch details using an intraoral camera.[40] One of the most common applications of digital workflow

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in clinical orthodontic practice is the CAD/CAM systems, where it has become popular in allowing the production of provisional dental restorations at a given clinical appointment.[39] Nevertheless, the limitations of the choice of materials, prosthesis duration, and reduced possibilities of veneering and customisation of the dental restorations are some of the drawbacks associated with digital workflow systems.[41]

A modified digital workflow has been recently proposed to address the aforementioned limitations, in which a virtual 3D model of the arch is generated using IOS and sent to a milling centre or manufacturing technicians to produce customised provisional dental restorations.[42] The advantage of this digital workflow is to support the skilled technicians, milling centres, and commercial dental laboratories in implementing the use of more durable materials; hence, ensuring that accurate proximal and occlusal contacts are achieved through longer span prostheses.[42] The IOS-generated image is then converted to STL file format that is then used to produce a physical cast by 3D printing that relates to the adjacent and opposing teeth, which dental technicians use to customise dental restorations.[15]

A quantitative clinical case study carried out by Piedra Cascón et al. [43] describes an analogue, and digital workflow from the CAD design of a digital template for the analogue fabrication of long-term interim injected composite resin restorations. The study employed a specific dental CAD software and SLA-AM printer to fabricate the diagnostic template, which was then used as a reference to prepare injected composite resin interim restorations. The main benefit of this approach represents the materialisation of the digital diagnostic waxing, where conventional waxing procedures are eliminated. Since the entire process is automated, it does not require most laboratory and clinical procedures such as exothermic heat phase of the material, residual monomers, and trimming or polishing the finishing lines in direct methods. This technique also eliminates the use of conventional master casts in indirect methods since the 3D models of the teeth could be prepared with more accuracy by injecting a light-body polyvinyl-siloxane impression material into the template to duplicate their copies.[43]

In clinical dental practices, this approach has been shown to improve laboratory workflow with minimal intervention of the lab technicians. The 3D printed diagnostic template provides a powerful tool for dental practitioners to visualise the digital diagnostic waxing in the patient's mouth and face. In addition, the diagnostic 3D printed template could be used for multiple applications in dentistry, including provisional restorations, radiographical, and surgical guide models in fabrication. The authors suggested that the fabrication technique provides a predictable workflow. Long-term injected resin composite restorations could be obtained from a 3D printed aesthetic diagnostic template; thus, improving the laboratory and chair-side procedures.[43]

The findings of this study have been supported by a recent study by Abduo[42] that compared the accuracy of casts produced from conventional and digital workflows. The traditional method of dental impression casts involved materials like whole arch alginate (ALG) and polyvinyl siloxane (PVS), whereas the digital workflows included casted images in the intraoral scanner (IOS) and laboratory scanner (LS). In this study, the results indicated that conventional impressions (ALG and PVS) were more accurate than digital models (IOS and LS) due to errors related to the span of scanning. The whole arch cast accuracies were highest for PVS, followed by LS, ALG, and IOS. It was reported that the digital impression casts from IOS and LS were considerably more affected at the posterior region of the teeth, particularly due to distorted material such as fossae and worn-out regions. However, the digital workflows (IOS and LS) had a higher single tooth accuracy compared to the conventional impressions.[42]

Conclusion

The recent advancement in digital dentistry has modernised both dental practices and dental laboratories by paving the way for computer-aided design (CAD) technology. The use of 3D printing has led to 3D digital models produced with intraoral scanners (IOS) and lab light scanners, which can be manipulated easily to conduct the required measurements to allow diagnosis and treatment planning for more predictable and efficient treatment of patients. It also eliminates the need for storage space but makes it easy to retrieve and transfer 3D models for use within all dental modalities. Overall 3D printing is a prime example of the fourth industrial revolution having a tremendously beneficial impact on patient care within dentistry.

Supplementary Materials: The following are available online at www.mdpi.com/xxx/s1, Figure S1: title, Table S1: title, Video S1: title.

Literature Search Details: The literature chosen was selected with eligibility criteria between the dates 1970 to the date the search was made on the 05/03/2019. The search was limited to;

- English language articles.

- Dental Literature

- Text searching for '3d AND printing OR print', 'additive AND technology', 'rapid AND prototyping', '3d printing AND materials', '3d printing AND accuracy', '3d print AND accuracy', 'history AND 3d AND printing', 'development AND 3d AND printing'.

- A manual search of the articles found and their respective references for other articles and reviews was also made.

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