International Journal Dental and Medical Sciences Research
Volume 4, Issue 6, Nov-Dec 2022 pp 89-98 www.ijdmsrjournal.com ISSN: 2582-6018

# Three-Dimensional Printing in Orthodontics: Acutting-Edge Technology

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Submitted: 01-11-2022 Accepted: 12-11-2022

**ABSTRACT**
3D imaging and modelling, and CAD technologies are hugely impacting all aspects of dentistry. 3D printing makes it possible to accurately make one-off, complex geometrical forms from this digital data, in a variety of materials, locally or in industrial centres. Even now, nearly everything we make for our patients can be made by a 3D printer, but no single technology is sufficient for all our patient's needs. The technology is already widely used in orthodontics, where high-resolution printing in resin is already an entirely practical proposition, and similar technology is being used to print models for restorative dentistry and patterns for the lost wax process which is becoming increasingly important with the rise of intraoral scanning systems. In maxillofacial and implant surgery, it is becoming commonplace and a prerequisite to use anatomical models made by any number of different 3D printing techniques to assist with the planning of complex treatments. Advancements in robotic bioprinters and robot-assisted surgery are integral to the evolution of this technology.
**Keywords:** 3D printing, orthodontics, anatomical models

## I. INTRODUCTION

The term Three- Dimensional(3D) printing is generally used to describe a manufacturing approach that builds objects one layer by layer at a time, adding multiple layers to form an object. This process is more correctly described as additive manufacturing or desktop fabrication, and also is referred to as rapid prototyping[1,2].Three-dimensional (3D) printing is a manufacturing method in which objects are made by fusing or depositing materials – such as plastic, metal, ceramics, powders, liquids or even living cells – in layers to produce a 3D object [3, 4, 5].

Some 3D printers are similar to traditional inkjet printers; however, the end product differs in that a 3D object is produced[3]. 3D printing is expected to revolutionize medicine and other fields, not unlike the way the printing press transformed publishing[3].Three-Dimensional printing involves the process of making 3-D solid objects from a digital file. The digital 3-D model is saved in STL format and then sent to the 3-D printer where the layer-by-layer design of an entire 3-D object is formed.

There are about two dozen 3D printing processes, which use varying printer technologies, speeds, resolutions, and parameters.[5,6] These technologies can build a 3D object in almost any shape imaginable as defined in a computer-aided design (CAD) file.[5] In a basic setup, the 3D printer first follows the instructions in the CAD file to build the foundation for the object, moving the print head along the x–y plane.[6] The printer then continues to follow the instructions, moving the print head along the z-axis to build the object vertically layer by layer.[7] It is important to note that two-dimensional (2D), radiographic images, such as X-Rays, magnetic resonance imaging (MRI), or computerized tomography (CT) scans, can be converted to digital 3D print files, allowing the creation of complex, customized anatomical and medical structures[7, 8, 9] (Fig.1).

The use of 3D printing technology in the field of medicine and dentistry is versatile to provide an individual product within a short period, which is tailored according to each patient.[10-12] Since one of the aims of contemporary medicine is to implement personalized medicine, the 3D printing technique should be applied to support such approaches as it provides a patient-specific product within a short time without sacrificing costs or benefits.[14] Forward-thinking orthodontic laboratories are finding ways to optimize their businesses and dental offerings to their clients through digital orthodontic dentistry and 3D printing.[13] Orthodontic laboratories can decrease labour-intensive and time-costly practices by adopting 3D printing, as well as increase profitability and efficiency.[1]

## HISTORY OF 3D PRINTING TECHNOLOGY

3D printing technology was introduced by Charles Hull which he termed "stereolithography" in 1980[16]. Stereolithography uses a .stl file format to interpret the data in a CAD file, allowing these instructions to be communicated electronically to the 3D Printer.[18] Along with shape, the instructions

International Journal Dental and Medical Sciences Research
Volume 4, Issue 6, Nov-Dec 2022 pp 89-98 www.ijdmsrjournal.com ISSN: 2582-6018

in the .stl file may also include information such as the colour, texture, and thickness of the object to be printed.[16]

Additive manufacturing or 3D Printing was founded in 1990 by Wilfred Vancraen, CEO and Director of Materialise NV, the first Rapid Prototyping sector company in the Benelux region.[17] 3D printing technology allows the user to create or "print" 3D physical objects, prototypes, and production parts of any shape from a virtual model in a growing range of materials including plastic, cobalt, nickel, steel, aluminium, titanium etc.[18,19] Those materials are joined in successive layers one on top of the other through additive processes under automated computer control. The 3D printing process usually begins with a 3D model, virtually designed or obtained through scanning of a physical object.

With time, 3D printers have significantly improved in terms of speed, possible component size and the precision of the components, which ultimately determines the fields of application. One example is the 3D printer from the company BEGO, which can currently be used to manufacture castable casting moulds (CAD/casting moulds), splints, drilling templates, individual moulding trays and models[12].

Additive manufacturing is likely to continue rapid growth in conjunction with intraoral scanning technology as a more effective system for orthodontic practices and laboratories for the automatic fabrication of high-resolution study models, retainers, metal appliances, aligners, and indirect bonding, accelerating the production time and increasing the capacity.[19,20]

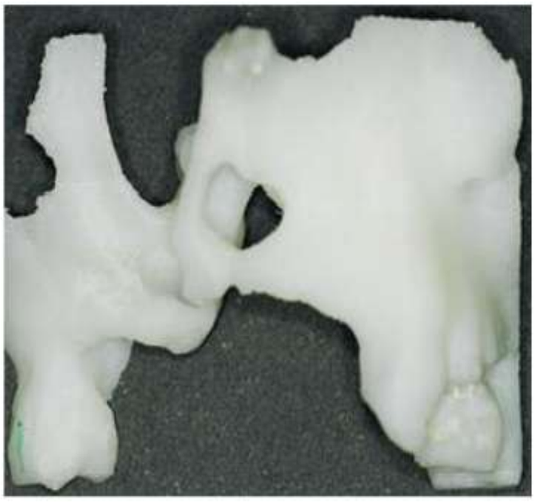

Fig. 1: The first patient treated by Dawood A[11] with the help of 3D printing in 1999 Frontal view of the 3D printed medical model, printed with Fused Deposition Modelling (FDM) technology, which shows the complex anatomy of the patient's cleft palate, before implant placement.

**Overview Of The 3d Printing Process**

Various additive technical processes are used to manufacture technical dental restorations. Generally, it involves the manufacture of semi-finished or finished parts. These are generated by joining, bonding, sintering or polymerising together small-volume elements.[12] Prerequisites for the application of 3D printing in dental medicine are a high degree of manufacturing precision and the use of medically harmless materials (Fig.2,3). The materials used must at least fulfil the requirements for class 1 medical products if they are to be placed in patients' mouths.[12]

**Fig.2: Example of a drilling template from 3D printing.**

**Fig. 3: Splint immediately after the 3D printing process with the printing base and support structure. The CAD design is done using 'Splint designer'. The implementation was performed in the CAM process using stereolithography.**

The steps of 3D printing technology include 3D modelling, preparation of data, Manufacture of objects and post-process. (Fig 4). Modelling of an object is done by the means of an intraoral 3D scanner, extraoral 3D scanner or cone beam computed tomography (CBCT). The obtained image is converted to a stereolithographic file (.stl file) by the means of CAD-CAM software

(Blender, 3Shape, Blue Sky Dental plan). Manufacturing of the object is carried out after the recognition of the .stl file by the printer. Finishing of the printed object can be done through heat treatment, curing with UV light and final polishing (Fig 4).

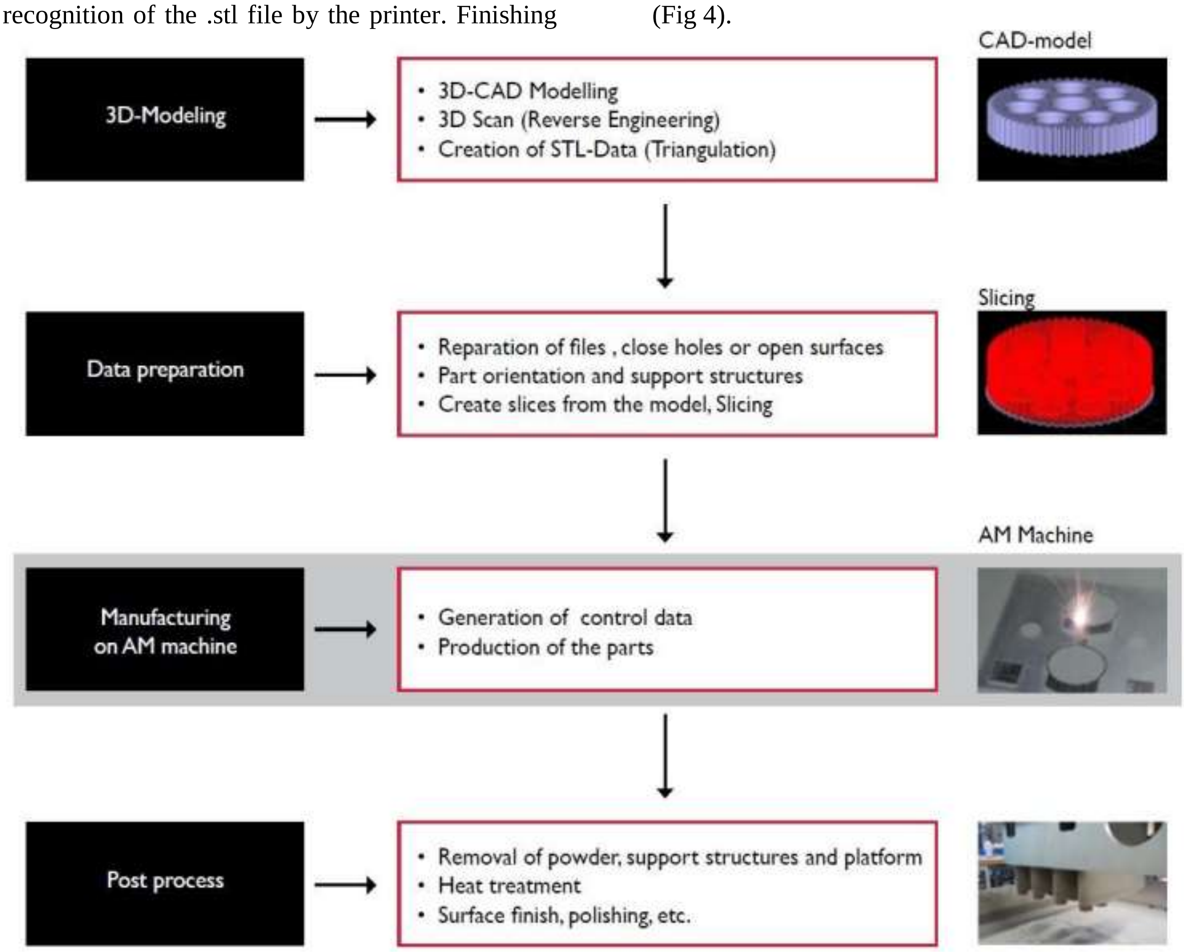


**Fig.4: Overview of the 3D Printing process**

**CLASSIFICATION OF 3D PRINTING TECHNOLOGY**

3D printing technology can be classified by the techniques, the materials or aimed deposition process:

**THE TECHNICAL TYPE CLASSIFICATION**

1. Stereolithography (SL)
2. Selective laser Sintering (SLS)
3. Direct metal laser sintering (DMLS)
4. 3D printing (Binder-Jet)
5. Electron Beam melting (EBM)
6. Fused deposition modelling (FDM)
7. Laminated Object Manufacturing (LOM)

**THE MATERIAL CLASSIFICATION**

1. Thermoplastic
2. Metal powder
3. Ceramic powder
4. Eutectic metals
5. Alloy metal
6. Photopolymer
7. Paper
8. Titanium alloys

Stereolithography (SL)

A stereolithography apparatus uses a scanning laser to build parts one layer at a time.[17,19] Each layer is traced out by the laser on the surface of the liquid resin, at which point a 'build platform' descends, another layer of resin is wiped over the surface, and the process is repeated. [11] The resolution of the built item is higher when more layers are used and the number of layers may range from 5 to 20 per millimetre.[17,19] After being built, objects are immersed in a solvent bath for excess resin removal and are consequently placed in a UV oven to finish the curing process.[21]

SLA models are currently used for planning cranial, maxillofacial, and neurosurgical procedures and constructing highly accurate replicas of human anatomy, customized implants, cranioplasties, orbital floors, and onlays. Surgical guides for dental implant placement are routinely produced by stereolithography.[21]

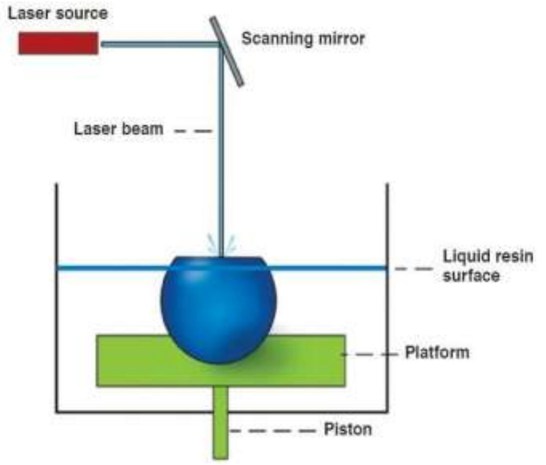


**Fig:5 Diagrammatic representation of Stereolithography**

**SELECTIVE LASER MELTING (SLM) AND SELECTIVE LASER SINTERING (SLS)**

A scanning laser fuses a fine material powder, to build up structures layer by layer, as a powder bed drops down incrementally, and a new fine layer of material is evenly spread[22, 23] over the surface. A high (60μm) level of resolution may be obtained, and as the structures that are printed are supported by the surrounding powder, no support material is required.[11]

They utilize uses power in the form of a high-energy laser beam directed by scanning mirrors to build three-dimensional objects by melting metallic powder and fusing the fine particles.[24] The laser energy is strong enough to allow full welding/melting of the particles to create a solid part. The process which can include partial and full melting or liquid phase sintering is recurring layer after layer until the object is completed.A broad range of metals and metal alloys available including titanium, titanium alloys, cobalt chrome alloys, and stainless steel can be utilized to fabricate 3D-printed partial dentures and prosthesis frameworks (Fig 6).

An SLS printer (Fig 7) uses powdered material as the substrate for printing new objects. A laser draws the shape of the object in the powder, fusing it. Then a new layer of powder is laid down and the process repeats, building each layer, one by one, to form the object.[15] Laser sintering can be used to create metal, plastic, and ceramic objects. The degree of detail is limited only by the precision of the laser and the fineness of the powder, so it is possible to create especially detailed and delicate structures with this type of printer.[15]

The 3D printing process itself may be straightforward, but post-processing is not straightforward, and the fine metal powders and even finer nanoparticle waste represent quite a significant health and safety challenge. While the printer itself may be readily accommodated in the dental laboratory, the associated post-production equipment takes up at least as much space. While in theory the use of one machine to print in different materials may seem feasible, in practice it is extremely difficult to fully clean down a machine, and certainly switching between an implantable metal and a restorative material is not at all practical.[11]

In small-batch production, the technology is costly and casting continues to have many attractions. However, in a large dedicated machine, it is possible to simultaneously print 400–500 crown copings in 24 hours. Furthermore, copings may be printed in lower-cost materials that are traditionally harder to work with than gold alloys, such as cobalt chrome, but which offer good porcelain bonding strengths and excellent mechanical properties.[11]

**Fig 6: A 14-unit bridge manufactured in the SLM process made from the alloy Wirobond C+**

**Fig 7: Selective laser Sintering 3D printer**

**BINDER JET**

The 3D printing system uses a print head to selectively disperse a binder onto powder layers. This technology has a lower cost than similar techniques. First, a thin layer of powder is spread over a tray using a roller similar to that used in the SLS system. The print head scans the powder tray

International Journal Dental and Medical Sciences Research
Volume 4, Issue 6, Nov-Dec 2022 pp 89-98 www.ijdmsrjournal.com ISSN: 2582-6018

and delivers a continuous jet of a solution that binds the powder particles as it touches them.[13]

The printing technique enables the formation of complex geometrical structures, such as hanging partitions inside cavities, without artificial support structures.[25] The printing and infiltration process takes approximately 4–6 hours. No support structures are required while the prototype is being fabricated because the surrounding powder supports the unconnected parts. When the process is complete, the surrounding powder is aspirated. In the finishing process, the prototype surfaces are infiltrated with a cyanoacrylate-based material to harden the structure.[26]

These printers can be used to identify different types of body tissue depending on the predefined threshold setting selected.[26] Silva et al. reported a mean dimensional error of 2.67% in prototypes produced using 3D printing technologies in comparison with a dry human skull.[26]

## FUSED DEPOSITION MODELLING (FDM)

FDM is one of the earliest 3D printing technologies and was used by Dawood A[11] to produce his first medical model in 1999. An FDM printer is essentially a robotic glue gun; an extruder either traverses a stationary platform, or a platform moves below a stationary extruder. Objects are ‘sliced’ into layers by the software and coordinates are transferred to the printer. Materials must be thermoplastic by definition. A commonly used material is the biodegradable polymer polylactic acid; these or similar materials have been used as key components of scaffold structures used for ‘bioprinting’[27] – a popular area for research in tissue engineering.

FDM employs the "additive" method of laying down thermoplastic material in layers. To produce a part, the material is passed through a heated nozzle after a metal wire or a plastic filament wound in a coil is released. The melted material hardens immediately after extrusion, thus minimizing inaccuracies[28]. The nozzle can be directed in both vertical and horizontal lines by a numerically controlled software mechanism (Fig 8). Several materials such as acrylonitrile butadiene styrene (ABS) polymer, polyphenyl sulfones and waxes, polycaprolactone, polycarbonates, polyamides, and lignin with diverse strength and thermal properties are available (Fig 9).[29]

FDM printers are much more common and inexpensive than the SLS type.[15] An FDM printer uses a print head similar to an inkjet printer.[15] However, instead of ink, beads of heated plastic are released from the print head as it moves, building the object in thin layers.[30] This process is repeated over and over, allowing precise control of the amount and location of each deposit to shape each layer.[30] Since the material is heated as it is extruded, it fuses or bonds to the layers below.[30] As each layer of plastic cools, it hardens, gradually creating a solid object as the layers build. Depending on the complexity and cost of an FDM printer, it may have enhanced features such as multiple print heads.[15] FDM printers can use a variety of plastics. 3D FDM printed parts are often made from the same thermoplastics that are used in traditional injection moulding or machining, so they have similar stability, durability, and mechanical properties.[30]

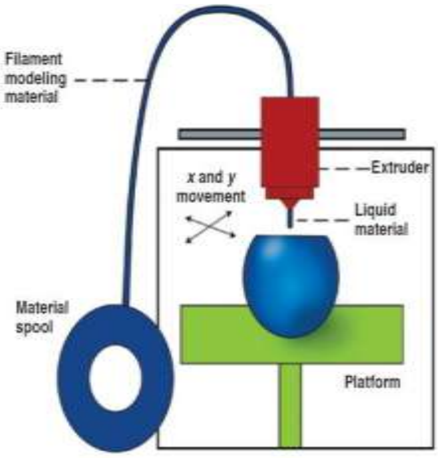


**Fig 8: Fused Deposition Modelling**

**Fig 9: Laying down the process of fused ABS polymer in typical FDM equipment.**

## ELECTRON BEAM MELTING (EBM)

Electron beam melting (EBM) is a type of additive manufacturing for laying down successive layers and creating near-net-shape or highly porous metal parts that are particularly strong, void-free, and fully dense (Fig 10). The EBM technology uses the energy source of an electron beam, as opposed to a laser.[31] Objects are manufactured layer by layer from fully melted metal powder utilizing a computer-controlled electron beam in a high vacuum. The technology operates at higher temperatures of up to 1000 °C, which could result in differences in the phases formed through solidification. EBM can form extremely porous mesh or foam structures in a wide range of alloys including stainless steel, titanium, and copper.[31] The technology is commonly used in orthopaedic and oral and maxillofacial surgery for manufacturing customized implants. Their structure permits the ingrowth of bone, provides better fixation, and helps to prevent stress shielding.[31]

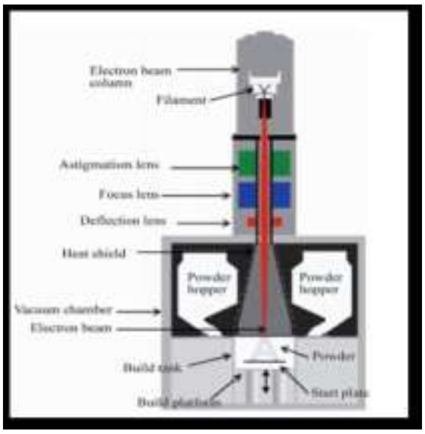


**Fig 10: Diagrammatic representation of Electron Beam melting**

**DIGITAL LIGHT PROCESSING (DLP)**

Digital Light Processing (DLP) is a type of nanotechnology that uses a digital micromirror device as a power source projector to cure liquid resin into solid 3D objects. DLP is similar to stereolithography as the method also employs light polymerization. One difference is that DLP creates a single layer as one digital image in tiny volumetric pixels as opposed to SLA's laser process which must scan the vat with a single point. DLP printing is faster and can build objects with a higher resolution, typically able to reach a layer thickness of fewer than 30 microns.[32]

Furthermore, DLP can produce objects with a wide variety of properties such as high clarity, springiness, flexibility, water resistance, thermal resistance, and durability. The photopolymers have been designed to mimic ABS, polypropylene, and wax, blending layers much more smoothly than plastic filament can. However, photopolymer prints can become brittle with increased light exposure over time. Objects may begin to show cracks and become more susceptible to breaking.[32]

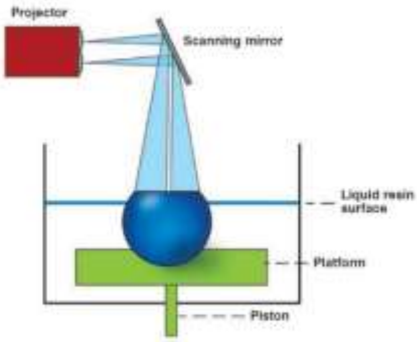


**Fig 11: Diagrammatic representation of DLP**

**LAMINATED OBJECT MANUFACTURING (LOM)**

Laminated object manufacturing (LOM) is a process that combines additive and subtractive techniques to build an object. It works by successively layering sheets of material one on top of another and binding them together using adhesive, pressure, and heat application.[33] Once the process is complete, objects are cut to desired dimensions with a knife, a laser, or additionally modified by machine drilling.The most common materials used in LOM are plastics, paper, ceramics, composites, and metals which are widely available and yield comparatively inexpensive 3D printing methods.[33] The technology can produce relatively large parts since no chemical reaction is necessary.[33] Surface accuracy is slightly inferior to stereolithography and selective laser sintering.[33]

**ORTHODONTIC APPLICATIONS OF 3D PRINTING**

Orthodontist creates beautiful smile and crafting smile is a time-consuming process. But with digitization, it has become easy. 3-D printing is revolutionizing the orthodontic process, providing digital advantages over the traditional workflow process. After the 3- D scan is done, it is transferred to the computer to get 3-D images of the patient's teeth. Either these files can be sent out to labs for fabrication or in the office set-up where the 3-D CAD file is dragged into the 3-D printer. Compact 3-D Printers companies (e.g.: Objet30 Orthodesk from Stratasys).[6]

The use of the technology to build dental models, removable appliances, customized brackets and archwires, and occlusal splints has been attempted and reported in the orthodontic literature. Currently, the most common application of 3D printers is for clear retainers and aligner fabrication. Practitioners can virtually move the teeth to a final ideal position, print a sequence of physical models in the office, and use a thermoplastic material to fabricate aligner trays, working on a similar premise to ClearCorrect and Invisalign. Skipping the step of 3D printing from a physical model, researchers have also used the technology to digitally design a retainer and consequently 3D print it in a fine while polyamide material.[34-37] Sophisticated software is further available for shaping and trimming the dental model base, for the design of bracket pads, hooks angulations, and guiding jigs.[34-37] Digital titanium Herbst, Andresen, and sleep apnoea appliances have been made with smooth surfaces, no sharp edges, and excellent fit on the teeth, palatal and gingival tissues.[34-37] Additive manufacturing enables features such as hinge production, building threads, and wire insertion to be completed in a single build without assembly.[34-37]

## 3D PRINTED MODELS

Going from an intraoral scan to a physical model is not as simple as pressing "print" on your computer. In most cases, the digital model will have tiny holes that need to be stitched, closed, and repaired before printing.[38] The software supplied with the printer is usually inadequate to prepare digital models, which require the aid of third-party CAD/CAM software such as NetFabb or Geomagic.[38] This kind of program can be used to extend the model base, remove excess material, imprint a patient identifier, and extract only what the operator desires to print. By making the interior of the printed model hollow, for instance, the program conserves expensive resin.[38]

Moreover, since printed models are seldom damaged in making retainers, replacements can easily be fabricated as needed, as long as the patient has been diligent with retainer wear.[38] At this time, the most common orthodontic application of 3D printers is for the fabrication of clear retainers and aligner trays. A CAD/CAM program such as Orchestrate 3D is used to create sequential virtual setups, which are sent to the printer for model fabrication.[38] Thermoformed aligners are easily made in the office using a material of the practitioner's choice. This cost-effective treatment is ideal for mild-to-moderate tooth movements, as compared to more expensive laboratory systems.[38]

## ACCURACY OF 3D PRINTING

Hazevald et.al[34] carried out a study to investigate the accuracy and reproducibility of physical dental models reconstructed from digital data by several rapid prototyping techniques.[34] The study concluded that dental models reconstructed by the tested rapid prototyping techniques are considered clinically acceptable in terms of accuracy and reproducibility and appropriate for selected applications in orthodontics.[34]

Camardella et.al[39] carried out a study to compare the accuracy of printed models from intraoral scans with different designs of model bases, using 2 types of 3-dimensional printing techniques. The study concluded that printed models with a regular base or a horseshoe-shaped base with a bar were accurate regardless of the printing technique used.[39] Printed models with a horseshoe-shaped base made with the stereolithography printer had a statistically significant reduction in the transversal dimension that was not found in the models printed with the polyjet technique.[39]

Papageorgiou[40] et.al evaluated the mechanical properties of resin-based materials as alternatives for the in-house preparation of orthodontic brackets. Two types of 3D-printed resins used for temporary (T) and permanent (P) crown fabrication were included in this study.[40] Ten blocks from each resin were manufactured by a 3D printer and, after embedding them in acrylic resin, the samples were subjected to metallographic grinding and polishing, followed by instrumented indentation testing (IIT).[40] Martens hardness (HM), indentation modulus ($E_{IT}$), and elastic index ($\eta_{IT}$) were determined with a Vickers indenter recording force-indentation depth curves from each specimen.[40] The study concluded that the mechanical properties of the two 3D-printed resins tested are equal, and thus, no differences in their clinical performance are expected.[40]

Kenning et.al[41] carried out an in vitro study to evaluate hollow 3D printed orthodontic models if there is an effect of shell thickness on the dimensional accuracy of retainers thermoformed upon them as compared with solid models.[41]The study concluded that 3D-printed model thickness affects the dimensional accuracy of a thermoformed retainer.[41] To ensure minimal deformation and promote the clinical utility of the thermoformed appliance, models should be printed with a minimum shell thickness of 2.0 mm.[41]

## BARRIERS AND CONTROVERSY

### 1. Unrealistic Expectations and Hype[8]

Despite the many potential advantages that 3D printing may provide, expectations of the technology are often exaggerated by the media, governments, and even researchers[8]. This promotes unrealistic projections, especially regarding how soon some of the more exciting possibilities—such as organ printing—will become a reality[8].

International Journal Dental and Medical Sciences Research
Volume 4, Issue 6, Nov-Dec 2022 pp 89-98 www.ijdmsrjournal.com ISSN: 2582-6018

2. **Safety and Security[8]**

3D printing has given rise to safety and security issues that merit serious concern. 3D printers have already been employed for criminal purposes, such as printing illegal items like guns and gun magazines, master keys, and ATM skimmers[8]. These occurrences have highlighted the lack of regulation of 3D printing technology[8]. In theory, 3D printing could also be used to counterfeit substandard medical devices or medications. Although 3D printing should not be banned, its safety over the long term will need to be monitored[8].

3. **Patent and Copyright Concerns[15]**

Manufacturing applications of 3D printing have been subject to patent, industrial design, copyright, and trademark law for decades.[15] However, there is limited experience regarding how these laws should apply to the use of 3D printing by individuals to manufacture items for personal use, non-profit distribution, or commercial sale.[15] Copyright is also an issue encountered in 3D printing. The fact that copyrights traditionally don't apply to functional objects beyond their aesthetic value may limit the significance in this area.[15]

4. **Regulatory concern[8]**

Securing approval from regulators is another significant barrier that may impede the widespread medical application of 3D printing[8]. Several fairly simple 3Dprinted medical devices have received the FDA's 510(k) approval. However, fulfilling more demanding FDA regulatory requirements could be a hurdle that may impede the availability of 3D-printed medical products on a large scale[8].

**FUTURE TRENDS**

3D printing is expected to play an important role in the trend toward personalized medicine, through its use in customizing nutritional products, organs, and drugs. 3D printing is expected to be especially common in pharmacy settings. The most advanced 3D printing application that is anticipated is the bioprinting of complex organs. Although due to challenges in printing vascular networks, the reality of printed organs is still some way off, the progress that has been made is promising. As technology advances, it is expected that complex heterogeneous tissues, such as liver and kidney tissues, will be fabricated successfully.

In Orthodontics, the most important advantage of 3D printing is that everything is customizable. Therefore, this technology may be most useful when the clinician needs to create a new device or prototype for precise treatment mechanics. For maximum accuracy and esthetics of customized retraction hooks, retainers, and aligner attachments 3D Printing will be useful and many current studies are going on 3D printing in Orthodontics will let more accurate and precise treatment results based on customized auxiliaries.

## II. CONCLUSION

With the rapid development and advanced research of diverse technologies and compatible materials, it is possible to obtain single scan digital impressions, virtual design, and 3D print different types of orthodontic appliances. 3D facial imaging further provides comprehensive analysis as an aid in orthodontics, maxillofacial, plastic, and aesthetic surgery. Software integration of digital models, 3D facial scans, and CBCT facilitate treatment simulations and establish meaningful communication with patients. Elimination of traditional impressions and dental-cast production stages enhances practice efficiency and patient and staff satisfaction for a fully integrated digital and streamlined workflow. Patient digital impressions are stored more conveniently and can be easily transferred to any lab or an in-office milling machine for a simpler, faster, and more predictable appliance fabrication. New companies, scanner and printer models are emerging daily which results in a significant decline in systems cost and enhancement of material qualities. From imaging to product design and manufacture, technologies will offer more affordable and feasible diagnostic and treatment applications beyond the current method.

Although 3D printers are becoming more affordable, the cost of running, materials, maintenance, and the need for skilled operators must also be carefully considered, as well as the need for post-processing and adherence to strict health and safety protocols. Despite these concerns, it is clear that 3D printing will have an increasingly important role to play in dentistry. The congruence of scanning, visualisation, CAD, milling and 3D printing technologies, along with the profession's innate curiosity and creativity makes this an exceptionally exciting time to be in dentistry.

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**LIST OF ABBREVIATIONS**

| | |
|---|---|
| 3D | Three dimensional |
| SL | Stereolithography |
| SLS | Selective Laser Sintering |
| DMLS | Direct metal laser Sintering |
| EBM | Electron-based modelling |
| DLP | Digital Light processing |
| FDM | Fused deposition modelling |
| LOM | Laminated object manufacturing |
| .STL | Stereolithographic file |
| CAD | Computer-aided designing |
| CAM | Computer-aided manufacturing |