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Review Article

3D-Printing in Fixed Prosthodontics: Lights and Shadows

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Abstract

Three-dimensional printing is an advanced additive manufacturing technology based on computer-aided design (CAD) digital models that has gained widespread acceptance in dentistry. It is highly efficient, reproducible, and provides fast and accurate results in an affordable manner, compared to conventional (lost-wax technique) and subtractive computer numeric controlled methods.

Nowadays, 3D printing is experiencing rapid development. It is often described as the key technology of the next industrial revolution.

The aim of this work is to explain its principle and to provide an up-to-date overview of the current materials, diverse techniques as well as its application in dental fixed prosthodontics.

Keywords: 3D-Printing; Prosthodontics; Shadows

Introduction

Three-dimensional printing is an advanced additive manufacturing technology based on computer-aided design (CAD) digital models. The technology uses standardized materials to create personalized 3D objects through specific automatic processes [1]. Three- dimensional printing has been widely used for rapid prototyping, design, engineering, and manufacturing fields for nearly 30 years [2]. With the rapid development of new materials, printing technologies, and machines, 3D printing is likely to completely change the traditional teaching and experimental modes [1,3].

In the field of medicine, such as traumatology, plastic surgery, and cranio-maxillofacial surgery among others, 3D printing is often used for digital imaging in surgical planning, custom surgical devices, and patient-physician communication. As for dental medicine, three-dimensional (3D) printing technology has changed the dentistry over the past decade. Its applications range from prosthodontics, oral and maxillofacial surgery, and oral implantology to orthodontics, endodontics, and periodontology [4]. 3D printing is a flexible technique that allows the fabrication of fully automated, personlaized treatment plans, thereby delivering custom-made dental devices and aids to the patients [5]. It is highly efficient, reproducible, and provides fast and accurate results in an affordable manner.

With the ongoing efforts of dental medicine specialistes, dental clinics are now shifting from conventional treatment methods to a fully digital workflow. In addition to its clinical success, 3D printing techniques are now employed in developing haptic simulators, precise models for dental education, including patient awareness [5].

Principle of 3D-dental printing

3D printing or additive manufacturing is a rapid manufacturing technique allowing the production of three-dimensional parts. It includes processes for manufacturing parts in volume by adding or agglomerating material, by stacking successive layers. The technique helps realize a real object thanks to a computer-aided design (CAD) tool. The 3D file obtained is processed by a specific software that organizes the slicing of the different layers needed to manufacture the desired part. The cut is sent to the 3D printer, which deposits or solidifies the material layer by layer until the final part is obtained. The first section of the part is consolidated by printing a polymer binder, then a roller spreads a thin layer of powder on the consolidated section and the second section is printed on the powder layer. And so on until the complete part is obtained. When the powder material is ceramic or metallic, thermal debinding and sintering cycles are required to burn the binder and weld the powder grains together by diffusion. The principle remains close to that of a classic 2D printer with this major difference: it is the stacking of the layers that creates the volume [1,7].

Production cycle

In order to produce a medical device using the digital chain, it is essential that the digital flow is processed in 3 distinct steps [8]

Data acquisition: 3D digitization

It corresponds to a double step of data acquisition from the intraoral environment (directly in the mouth or on supports: impression or model) and then to a transformation of these data into a digital flow exploitable by the computer systems of the following steps. In CAD/CAM, the cast is not physical but digital. The first step of the digital chain consists in acquiring a set of data from the patient's intraoral environment and converting them into digital data that can be used by computer systems. The 3D digitization is performed with the help of devices called 3D scanners [9].

Intraoral digital impression using an intraoral scanner

An intraoral scanner is an electronic device for taking so-called digital scans (impressions) of intraoral structures by means of contactless scanning with light rays (visible light/laser) chairside and within seconds or minutes. These devices comprise a wired handpiece, for intraoral use by the dentist, connected to a computer system with a monitor.

A combination of a special camera unit in a known three-dimensional position to a light source uses triangulation to calculate the three-dimensional arrangement of the light reflecting surface points of the scanned structures with an accuracy of 20 µm. Each measuring field is usually only about two square centimetres in size, but many images (20 to 60 mostly colour video/series images per second) can be taken and merged in quick succession [10].

Intraoral scanners are an increasingly relevant alternative to taking conventional impressions with elastomeric impression materials (Polyvinyl Siloxane (PVS), polyether, etc.). Less material is required, breathing is not obstructed and gagging as well as risk of aspiration no longer occur. This very first important step already provides an entry-point to digital workflow, without having to "divert" via error-prone "real" impressions and models followed by scanning them with extraoral equipment ("lab scanners") [10].

Extraoral digital impression

Done generally in the laboratory in which the dental technician proceeds to scan the dental plaster cast model (obtained through the conventional way at the dentist's office) with a digital scanner in order to obtain the 3D impression file in the laptop [10].

Computer aided design (CAD)

Computer Aided Design (CAD) refers to all software using geometric modeling methods to design and virtually simulate the behavior of a prosthesis. It allows the creation of 3D models in a virtual environment subject to the laws of physics [11].

Once the master cast is obtained, the operator can digitally model the future prosthesis (CAD). The working model appears in 3 dimensions. It can be seen from all angles and all sizes. It can be trimmed, corrected, the spacing varnish for the cement/glue can be simulated, the limits can be taken over. The CAD software has pre-forms that are adapted according to the prosthesis to be made, the shape of the patient's teeth, the limits and the occlusion are predefined by the dental technician. Once the design is finished, the object to be printed is transferred to the 3D printing software which will cut it into layers to make the prosthesis [6,12].

Computer aided miling (CAM)

This technique was developed to create files containing standardized instructions for all the movements that must be performed by the moving parts of a machine tool in order to produce a part from a 3D model. In fact, CAM is the link between the CAD software and the material forming machine. In mechanical manufacturing, the term "control" is used to describe all the hardware and software required to control all the components of a machine tool via various movement instructions. CAM software, unlike CAD software, is dependent on and even specific to the manufacturing process under consideration (subtractive or additive) [6,12].

Materials used in the manufacturing process

Raw materials for dental additive manufacturing can be classified into binder/powder material combinations, including polymers, ceramics, and metals [13].

Polymers

Additive manufacturing machines use polymers as raw material for building programmed structures. Polymers include a wide variety of substances such as Acrylonite Butadiene Styrene (ABS), Polylactic acid (PLA), Polyethylene terephthalate (PET), the polyester, polyether-ether-ketone, wax, resin... [1,3].

Metal

The use of Cobalt-Chromium (CoCr) base metal in the substructure of dental prostheses has become a popular option because of the increased cost of precious alloys and the economic pressure on patients.

Not only does metal have an advantage over precious alloys in terms of cost, but it also has good adhesion characteristics with ceramics, higher Young's modulus, higher hardness, lower density and good corrosion resistance compared to other metals [14].

Ceramics

CAD/CAM ceramic materials evolved from traditional feldspathic porcelain. They provide an aesthetic outcome, but they are low-strength, brittle materials. Ceramic range of materials vary according to strength, resilience, and esthetic properties [14].

Additive manufacturing technologies 4.1The photo polymerization in tank

According to the definition of the ISO 17296 standard, it is « a manufacturing process in which a liquid photopolymer immersed in a tank is cured in a way by light-activated polymerization ». This technique is characterized by the use of photopolymerizable liquid polymers (photopolymers) [9].

Stereolithography (SLA)

It is a 3D Printing process that uses a computer-controlled moving laser beam, preprogrammed using CAM/CAD software. The SL machine starts the 3D printing process by drawing the layers of the support structures, followed by the part itself, with an ultraviolet laser aimed onto the surface of a liquid thermoset resin. After a layer is imaged on the resin surface, the build platform shifts down, and a recoating bar moves across the platform to apply the next layer of resin. The process is repeated layer by layer until the build is complete [12,16,17].

Digital light processing (DLP)

DLP is a 3D printing technology used to rapidly produce photopolymer parts. It is very similar to SLA with one significant difference: where SLA machines use a laser that traces a layer, a DLP machine uses a projected light source to cure the entire layer at once [15,18].

Continuous liquid interface production (CLIP)

The process starts with a pool of liquid photopolymer resin. Part of the pool bottom is transparent to ultraviolet light (the "window"). An ultraviolet light beam shines through the window, illuminating the precise cross-section of the object. The light causes the resin to solidify. The object rises slowly enough to allow the resin to flow under and maintain contact with the bottom of the object. An oxygen-permeable membrane lies below the resin, which creates a "dead zone" (persistent liquid interface) preventing the resin from attaching to the window (photopolymerization is inhibited between the window and the polymerizer) [19].

Powder bed fusion (PBF)

It is an additive manufacturing, or 3D printing technology that uses a heat source, typically a laser, to sinter or fuse atomized powder particles together. Like other additive processes, this is done one layer at a time until the part is completed [20].

Material extrusion 3D printing technology

It uses a continuous filament of a thermoplastic material as a base material. The filament is fed from a coil, through a moving heated printer extruder head, often abbreviated as an extruder. The molten material is forced out of the extruder's nozzle and is deposited first onto a 3D printing platform, which can be heated for extra adhesion. Once the first layer is completed, the extruder and the platform are parted away in one step, and the second layer can then be directly deposited onto the growing workpiece [21]. The extruder head is moved under computer control. At least three axes are required for the extruder to move in Cartesian architectures, but polar and delta systems are also becoming increasingly popular. One layer is deposited on top of a previous layer until the object's fabrication is complete [17].

The material jetting 3D printing

It is often compared to the standard 2D ink jetting process. It uses photopolymers, metals, or wax that solidify when exposed to light or heat (in a similar fashion to stereolithography) ensuring that physical objects are built up one layer at a time. The material jetting manufacturing process allows for different materials to be 3D printed within the same part. Material jetting dispenses a photopolymer from hundreds of tiny nozzles in a printhead to build a part layer-by-layer. This allows material jetting operations to deposit build-material in a rapid, line-wise fashion, which can be compared to other point-wise deposition technologies that follow a path to complete the crosssectional area of a layer, also called a slice. As the droplets are deposited to the build platform they are directly cured and solidified using UV light. Material jetting processes require support, which is often 3D printed simultaneously during the build from a dissolvable material. The support material is then removed during the post processing step [12,17,22

The application in the dental fixed prosthodontics

Study/work casts

The printing of study/work models using a CAM process is currently one of the main applications in dentistry. The dental technician receives either a digital impression or a traditional physico-chemical impression which he digitizes. He/She will define the cutting limits of the "die".

The virtual model can be printed directly by an additive machine tool, without requiring an operator during its realization. Once the model is printed, the traditional procedures of realization of traditional prosthesis can be carried out. The model can be a full arch, a half-arch or a smaller block; it is also possible to make the stumps removable [23].

Rapid prototyping and morpho-functional therapeutic project (RPMFT)

Through the production of resin casts to carry out directing assemblies and validate therapeutic projects at all therapeutic steps such as

- **Bite correction:** The pre-prosthetic study is often essential to the proper conduct of our treatments, especially when the occlusal reference position must be modified.

In order to evaluate the patient's acceptance of this new position, a temporization phase by assembling temporary crowns or overlays must be integrated into the treatment plan. It is now possible to perform this study phase digitally. The modifications are made directly on the digitized models of the dental arches, in the form of a "digital wax-up". If indirect iso molding is chosen to transfer this prosthetic project into the mouth, the materialization of the modified models will be done using 3D printing [24].

- **The Vertical Dimension of Occlusion (VDO) adjustment:** It is possible to make digital wax-ups directly on the patient's model. This new model is then printed and a silicone impression is made to transfer it into the mouth as a mock up. In addition to the usual time and precision savings, several wax-ups can easily be printed quickly and inexpensively until the ideal DVO and/or occlusion setting is found. The dental technician only has to modify the digital wax-up according to the practitioner's instructions and sends it back to production [25].
- **The approval of the esthetic project:** In the same way, we will be able to print models to make mock-ups for veneers, dental or implant-supported prostheses and make modifications to validate the project with the patient [25].

Temporary dental crowns and bridges

Temporary prostheses can be 3D printed with biocompatible resins from a 3D model obtained by 3D scanning of the patient's dentition and are perfectly fitted to the patient's mouth thanks to the high precision of 3D scanning and SLA or DLP 3D printers. In the case of emergency treatments, it is for example possible to 3D print temporary dental crowns in a short time.

Additive manufacturing avoids the disadvantages of the direct technique as well as subtractive manufacturing. Indeed, the exothermic heat generated during the polymerization of the resin in the direct method can cause thermal trauma to the dental pulp. Furthermore, the residual resin monomer could damage the oral mucosa, causing lichenoid reactions or allergic stomatitis. Another drawback of the direct method is the shrinkage of the resin caused by the reduced atomic distance in the low molecular weight monomers used. This shrinkage leads to dimensional differences in the marginal, interproximal and occlusal regions. In the milling method, an object is fabricated subtractively using cutting burs. As a result, the size of the cutter and the range of cutting motion are limiting factors in fabrication. When an object has sharp edges or a rough surface, it cannot be reproduced by the milling method [26].

Manufacture of calcinable casts for lost wax casting

Conventionally, the lost wax casting technique is a molding process from a wax sculpture. Here we no longer speak of sculpture as was the case for the manual achievements of prosthetists but of printed models. The latter can be in wax but are more frequently in calcinable resin because it is easier to print. The latter are made on computer, printed in 3D, and then heated in order to melt the wax object to obtain a hollow space of the exact shape of the desired dental prosthesis. The final object is created by injecting a specific material into the mold. This method can be used to make copings for metal crowns and bridges as well as molds for pressed ceramic crowns, which require a burnout model [27].

Direct manufacturing of metal dental prostheses

Metal 3D printers are based on powder sintering technology and use metal powders, such as bio-compatible cobalt powder, as consumables. Metal 3D printers are increasingly used in dentistry for the production of finished dental prostheses and implants for several reasons [28]

Standardization of dental prosthesis manufacturing.

- Reduction of the time and complexity of the production cycle of dental prostheses and implants with a high quality and a lower cost.
- It is also possible, after the printing of the coping for a single crown or the framework of a bridge, to carry out the ceramization in a conventional way in order to obtain a classic metal-ceramic crown [25].

Direct manufacturing of ceramic dental prostheses

Ceramic 3D printing is a relatively new technology. It is currently being used in the automotive and aerospace manufacturing sectors to create parts with adequate heat absorption, high hardness and corrosion stability [29].

Typically, ceramic printing is a secondary printing process, where a burnable resin screen is printed onto which the unsintered ceramic is bonded [30].

Currently, 3D printing of ceramic blanks is still in the research and development stage. Two recently exposed technologies are capable of achieving: lithography-based ceramic manufacturing (LCM) as well as nanoparticle jetting (NPJ) [29].

The application in implantology

Custom 3-D bone allograft block fabrication

Additive manufacturing has made possible in recent years the development of a process leading to the elaboration of a cancellous or cortico-cancellous graft used in pre-implant apposition surgery. Despite the high cost of these technologies, they permit the customization of the procedure as well as the "ideal-fitting" graft to host tissue. The reported disadvantages include cost, extre wait times, and the potential lack of blood supply within the custom bone block. Nevertheless, ongoing research has continued to investigate their potential uses [25,30].

Dental surgical guides

Definition

Surgical guides help dentists place dental implants properly and in the right locations. They are developed by imaging software that creates a remapped plan, which aims to create a seamless dental implant process. In order to create a surgical guide, impressions are taken at the desired surgical impact site, including 3D images (DICOM files) obtained after a Dentascanner or CBCT scan [30]. These impressions and imaging are then transferred to special software that develops the guide device. These devices, similar to a clear retainer, are then placed over the patient's teeth and the dentist can easily find the area where the implant should be placed [30].

Protocol

Data acquisition

3D maxillo-mandibular bone imaging is acquired through a denta-scanner or Cone Beam which includes very precise information but above all an examination surface that is sometimes too large in view of the working area that concerns us. We must therefore define this area in the three planes of space.

Import of STL data: from an optical impression in the mouth or obtained secondarily by digitizing conventional casts with a laboratory scanner.

Matching: STL and DICOM files are digitally superimposed with the help of easily identifiable dental landmarks (cusps, marks…).

Prosthetic project modeling

The modeling of the future implant placement is designed according to the available prosthetic space, the gingival height and the occlusal relationship with the antagonist and adjacent teeth. Implant positioning and length take into account bone volume, density and quality. The prosthetic abutment is modeled according to the implant axis, the gingival height and the type of prosthesis. The implant (s) to be placed are selected from a library of references from different brands.

The position of the chosen future implant is validated, then appears on the various sections and it is then possible to place it in the three dimensions of space more precisely [15].

Choice of the future guide bush/cylinder

Once the position is validated, it is then possible to choose the guide cylinder(s). These 5mm diameter drill bushes are positioned taking into account the gingival height, the position of the tooth to be replaced, the type and length of the implant. They guide the axis of the implantation and serve as a height marker during the various stages of drilling. The higher the socket, the longer the drill bit. An implant with a supraosseous emergence requires a higher position of the sleeve. An implant in the posterior sectors requires a lower socket position with a shorter implant length to limit the length of the drills in a way that is compatible with the patient's oral opening [15].

Delimitation of the future guide

The first step is to define the teeth and/or the support surfaces. Then refining the limits in order to reduce the risks of interference or tilting [31].

Visualization of the final project

A request for validation of the future surgical guide will appear. It is then possible to send the global file including all the data we have worked with or simply the STL file of the future guide [31].

3D printing of the surgical guide

The model of the dental arches and the guide are 3D printed. The metal sleeves are then inserted and fixed by friction [6,31].

Conclusion

The rapid evolution of CAD/CAM techniques and the popularization of 3D printing are having a huge impact on dental practice.

With its wide range of techniques and materials, which meet the specifications in terms of biocompatibility, strength and aesthetics, 3D printing makes it easy to produce small, precise and custom-made objects, which is perfectly in line with the requirements of dentistry.

The development of the dental market is promising, and that maximum benefit can be derived from additive manufacturing techniques.

In fixed prosthetics, it is currently possible to produce various prosthetic elements, study models, temporary prostheses and surgical devices to guide the procedure.

It is also possible today to 3D print polycrystalline ceramics (zirconia, alumina...).

The tedious steps are reduced, the quantities of raw material used are reduced and the finishing steps of the parts are simplified, which is not possible with machining.

One of the biggest revolutions to be expected is in tissue engineering, which will go hand in hand with "bio-printing" to produce bone substitutes. This technology depends on matrices to maintain the tissue structure. However, in the esthetic field of dentistry 3D printing is not only offering more adequate and precise tools for the esthetic project but it also allows more consevative technical procedures regarding ceramics. Further research needs to be performed to prove that printing ceramic is a secure future for an optimum esthetic dentistry.

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