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An update of additive manufacturing (3D printing) technology in dentistry.

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REVIEW ARTICLE / *REVUE DE LITTÉRATURE*

Dental Technology / *Technologie Dentaire*

AN UPDATE OF ADDITIVE MANUFACTURING (3D PRINTING) TECHNOLOGY IN DENTISTRY

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Background: The development of procedures known as additive manufacturing, which aim to produce more complex items with a lower overall material consumption compared to processes known as subtractive manufacturing. In addition, in recent years there has been a significant rise in the quantity of dental materials that are produced via the use of these techniques. As a consequence of this, scientific research has been concentrating more and more on such technologies, particularly in order to shed light on the methodology, indicators, and boundaries of the emerging technology.

Methods: The purpose of this paper is to provide a narrative assessment of the state-of-the-art in the area of these popular additive manufacturing methods, as well as the appropriate dental applications, by using scientific literature analysis and references to the authors' clinical experience. In addition, the purpose of this study is to evaluate the appropriate dental applications. \

Results: The end result was a tremendous amount of data, most of it is conflicting, is now available for viewing. In tests conducted both in vitro and in vivo, the following additive manufacturing procedures were shown to be effective: Milling results in a number of negative side effects, including the loss of material, increased costs associated with equipment maintenance, and wasted production time. Additive manufacturing, often known as 3D printing, allows for the production of prostheses and models at a quicker rate and with less waste material.

Conclusions: In order to successfully manufacture complex component geometries, CAM configuration and process design must be carefully considered. As a consequence of this, the speed at which the process is carried out is of equal importance to the interaction between the individual components. When dealing with geometry that is more complicated, 3D printing beats CAM.

Keywords: additive manufacturing, 3D printing, computer-aided manufacturing (CAM) -computer-aided design.

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The authors declare no conflicts of interest.

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UNE MISE À JOUR DE LA TECHNOLOGIE PAR FABRICATION ADDITIVE (IMPRESSION 3D) EN DENTISTERIE

Contexte: Le développement de procédés dits de fabrication additive, vise à produire des objets plus complexes avec une moindre consommation globale de matière par rapport aux procédés dits de fabrication soustractive. De plus, ces dernières années, il y a eu une augmentation significative de la quantité de matériaux dentaires produits grâce à l'utilisation de ces techniques. En conséquence, la recherche scientifique se concentre de plus en plus sur ces technologies, notamment afin de faire la lumière sur la méthodologie, les indicateurs et les limites de cette technologie émergente.

Méthodes: Le but de cet article est de fournir une évaluation narrative des nouveautés dans ce domaine des méthodes de fabrication additive, qui devient de plus en plus populaire, ainsi qu'une évaluation des applications dentaires appropriées, en utilisant une analyse de littérature scientifique et une référence aux expériences cliniques des auteurs. De plus, le but secondaire de cette étude est d'évaluer les applications dentaires appropriées.

Résultats: Le résultat final était une énorme quantité de données, la plupart d'entre elles étant contradictoires, qui sont maintenant disponibles pour visualisation. Lors de tests menés à la fois in vitro et in vivo, les procédures de fabrication additive se sont révélées plus efficaces, sachant que le broyage entraîne un certain nombre d'effets secondaires négatifs, notamment la perte de matériau, l'augmentation des coûts associés à la maintenance de l'équipement et la perte de temps de production. La fabrication additive, souvent connue sous le nom d'impression 3D, permet de produire des prothèses et des modèles plus rapidement et avec de perte de substance.

Conclusion: Afin de fabriquer avec succès, des formes géométriques complexes, la configuration FAO et la conception du processus doivent être soigneusement prises en compte. En conséquence, la vitesse à laquelle le processus est exécuté est d'une importance égale à l'interaction entre les composants individuels. Lorsqu'il s'agit de formes géométries compliquées, l'impression 3D l'emporte sur la FAO.

Mots clés : Mots clé: fabrication additive, impression 3D, fabrication assistée par ordinateur (FAO) -conception assistée par ordinateur

IAJD Vol. 14 – Issue 1

Introduction

Complex parts can be machined with computer-aided manufacturing (CAM) straight from computer-aided design (CAD) data, though the process is subtractive rather than additive. Machining using computer-aided design (CAD) requires a material block at least as big as the finished product. Three-dimensional printing involves the use of powders and liquids to create an object that is at least one dimension larger than the feedstock [1].

Generally speaking, CAM machining is able to produce materials at a much faster rate than 3D printing machines [2]. Since a part can be made with 3D printing in a single step, this is only part of the story. Particularly as part geometries become more complex, CAM machines demand meticulous setup and process planning. As a result, the rate of the process is as important as the material's physical interaction with the part [3].

The advantages of 3D printing over CAM become more pronounced with increasing geometric complexity. The drawbacks of the milling method include excessive material loss during milling, high equipment maintenance costs, and significant time loss during the production process. On the other hand, the advantages of 3D printing include the production of desired prostheses and models with the lowest amount of material and the capability to construct multiple products at a time [4].Some geometric features may be infeasible to fabricate if CAM is used to create a part directly in a single piece. Machining tools are typically housed in a spindle, which can create accessibility issues or collisions when trying to position the tool on the part being machined. Due to the unrestricted nature of 3D printing processes, internal and external undercuts can be constructed with little to no advance preparation. Some components require disassembly for CAM fabrication, then reassembly at a later time [5].

3D printing or additive manufacturing is a method of producing three-dimensional solid objects from a digital file. In an additive process, an object is created by laying down successive layers of material until the entire object is created. Each of these layers can be thought of as a thinly sliced horizontal cross-section of the final object [6].

Using 3D printing technology, a three-dimensional solid object is printed in three dimensions using computer-aided design (CAD) data. 3D printing is finding applications in industries as diverse as aerospace, visual arts, medicine, and dentistry. 3D printing is used in dentistry for a variety of purposes, including surgical guides, provisional dental restorations and detachable prosthetic devices, and dental casts [7].

Thanks to the efforts of Charles Hull, 3D printing techniques were made available to the public in 1980. By exposing thin layers of photopolymer to a focused UV light beam, complex three-dimensional geometries were created. Since then, a variety of technologies and materials have been incorporated into thin layer printing [8]. Aside from the ability to print in a wider range of shapes, 3D printing also offers a more conservative approach, increasing accessibility to the point of consumption and lowering labor costs [9]. Some of the applications of 3D printing in dentistry include drill guides for dental implants, physical castings for prosthetics, orthodontics, and surgery, dental, craniomaxillofacial, and orthopaedic implants, and copings and frameworks for implant and dental restorations. It is possible to create a precise virtual model of the prepared tooth, implant position, and dental arch using intraoral scanners or laboratory scanners. CAD software can be used to plan treatment and design restorations in both permanent and removable prosthodontics. The scan data and CAD design can be used to mill or print crowns, bridges, and implant abutments [10].

Different Types of 3D Printing

1- Vat Photo Polymerization

The most common method of 3D printing in the form of photopolymerization is laser or UV light curing of photo-reactive polymers [11]. Stereolithography and digital light processing are two vat photopolymerization-based 3D printing technologies. The resolution is affected by the photo initiator and irradiation exposure conditions, as well as any dyes, pigments, or other UV absorbers that may be added to the stereolithography process [12]. In contrast, stereolithography employs photopolymers in a manner similar to digital light processing. It makes a big difference where the light comes from.

The Digital Light Process employs traditional light sources such as arc lamps and liquid crystal display panels. Because it can cover the entire photopolymer resin vat in a single pass, it is faster than stereolithography [13].

Exposure time, wavelength, and power supply all play important roles in Vat Photopolymerization. When exposed to ultraviolet light, the liquid hardens into a solid. Photopolymerization is the best option for producing a premium product with fine details and a high surface quality [13].

- Stereolithography (SLA):

Stereolithography is a photopolymerization process that produces multilayered solid objects by using an ultraviolet (UV) laser to solidify liquid-based materials. Stereolithography printers have grown in popularity in recent years due to their ability to produce structures with resolutions as low as 10 microns. When SLA monomers are exposed to UV light, they start forming polymer chains. Polymerization creates a pattern in the resin layer that serves as the basis for subsequent layers. Following the printing process, the unreacted resin is removed. During this post-processing step, isopropyl alcohol is used to clean the structure before curing it with UV light [14].

The main limitation of stereolithography has been identified as a lack of commercially available resins for processing. When exposed to light, the resin should instantly solidify. Because of their ability to polymerize and crosslink when exposed to light, low-molecular-weight polyacrylate or epoxy macromers were used in early stereolithography resins. After curing, the networks formed by various resins have mechanical properties that allow them to be used in a variety of applications. Because of the ongoing improvement in the quality of stereolithography parts, they can be used not only as prototypes, but also as functional components for increasingly demanding end-use applications [15]. In most stereolithography resins on the market, low molecular weight, multi-functional monomers produce highly cross-linked networks. These materials are mostly brittle, glassy, and stiff. Only stereolithography and a few resins can be used to create elastomeric objects [16, 17].

The final objects have a diverse range of qualities due to the wide variety of resins that have been processed using stereolithography. This method allows you to use only one resin at a time, regardless of how many resins are available. Fused deposition modeling 3D printing and plotting procedures enable the use of multiple cartridges to produce structures made of various materials at the same time. Stereolithography can pattern multiple resins for each layer built, though the process requires complex sequential polymerization and washing procedures [17, 18]. Uncured resin removal and reservoir replacement necessitate the development of an automated system capable of removing and replacing resin reservoirs automatically. Stereolithography has a significant disadvantage in that only one resin can be used at a time [19]. NextDent C&B Vertex Dental and other manufacturers provide commercially available stereolithographically produced resins (Temporis; DWS, thiene, Italy).

- Digital light processing (DLP):

Digital light processing (DLP) is an example of 3D printing that uses UV light to polymerize materials and construct pre-designed structures [20]. When compared to extrusion-based and inkjet-based 3D printing methods, this one has significant advantages in terms of printing resolution, efficiency, and working conditions. As a result, products can have a wide variety of useful features. Because of their shape and physical properties, medical models are ideal for simulating the human body. The incorporation of beneficial structures into implants can aid tissue regeneration. Artificial tissues and organs with precise bionic structures and high cell viability are also being developed. Customized drug delivery systems enable accurate dosing, controlled release, and minimally invasive administration [21, 22, 23, 24]. DentalTOOTH and TEMP are two commercially available printed resins that use digital light processing (Asiga, Sydney, Australia). The differences between SLA and DLP 3D printing are shown in Table 1. The following table compares SLA and DLP methods.

- Liquid crystal display (LCD):

The imaging system is the most significant difference between DLP and LCD 3D printing technology. In the LCD 3D printing technique, the liquid crystal display is used as an imaging system. When an electric field is applied to a liquid crystal, it will change its molecular arrangement and prevent light from passing through. The resolution of the liquid crystal display is very high. Yet, during the electric field switches, a small number of liquid crystal molecules cannot rearrange, resulting in weak light leakage. This caused LCD printing technology's precision to be inferior to the DLP [25].

	SLA	DLP
Light source	**UV laser beam**	**UV light from a projector**
Accuracy	More accurate; the curing (hardening) of the resin is done from point to point.	Less accurate; light source remains stationary and it cures the complete layer of resin at a time.
Speed	**Slower**	**Faster**
Intensity of the light source	The intensity of the laser beam cannot be adjusted and you have to change the laser light completely for different resin effect.	Operator can control the intensity of UV light source and thereby control its effect on the resin.
Cost	**More expensive**	**Less expensive**
Uses	Useful to print a large part with intricate details.	Useful in quickly printing large part without much detail

Table 1: Comparison between SLA and DLP

2- Binder jetting

Binder jetting is a process that uses a powder and a binder. An organic binder, which is frequently a liquid, holds ceramic powder particles together (the building material). A print head moving horizontally along the machine's x and y axes alternately deposited the construction material and the binding substance. To continue building, the construction platform must be lowered after each successive layer [26].

Binder jetting allows you to print with a wide variety of materials (metal, polymer, and ceramics) and powder/binder combinations, and it is also a quick procedure [27]. The primary disadvantages of this method are high porosity and, as a result, low mechanical properties of printed parts. Binder jetting is heavily reliant on the powder's ability to flow and distribute. Using powders with large particle sizes can improve flowability, but this can have a negative impact on sintering and densification after printing. Agglomeration and impaired flowability, on the other hand, are common side effects of extremely small particle size [27].

3- Material jetting

Material jetting is the process of depositing droplets of build material that are selectively dispensed through an orifice to build up a 3D structure using inkjet printing or other similar techniques [28]. After deposition in material jetting processes, liquid material (in the form of a droplet) frequently solidifies due to cooling or chemical changes (e.g., polymer cross-linking or solvent evaporation) [29].

4- Fused deposition modeling (also known as Material Extrusion)

A nozzle is used in the extrusion process to expel the heated material. After that, it is applied in layers, one on top of the other. The build platform and nozzle can both move vertically and horizontally to accommodate the addition of additional layers [26].

Fused deposition modeling has some drawbacks, including being slower than other additive manufacturing processes and having less precision due to nozzle radius constraints, resulting in a lower-quality final product [26].

5- Powder bed fusion

Thermal energy is used to melt the powder into the desired pattern when a powder-bed-fusion machine is used, similar to how binder jetting machines work [28]. Laser energy can be used to melt polymers, metals, and ceramics. A technique known as Selective Laser Sintering allows for partial melting. This method of melting is known as selective laser melting (SLM). Electron Beam Melting is another method for melting metal powder that uses an electron beam. Powder properties (such as particle shape and particle size) are governed by process parameters such as energy source, energy power, spot size, scan speed, spacing distance, and layer thickness [30].

6- Direct energy deposition

Materials can be melted as they are deposited using directed energy deposition methods. This basic method is most commonly used with metal powders, but it can also be used with polymers, ceramics, and metal matrix composites. The process by which this technology is used is referred to as metal deposition [4].

In directed energy deposition methods, materials are not pre-melted in a powder bed, but rather melt as they are deposited. Directed energy deposition technologies (like extrusion-based procedures) use a focused heat source to melt the feedstock material and build three-dimensional objects (usually a laser or electron beam). Each pass of the directed energy deposition head creates a hardened material track, and the material lines adjacent to it form layers. The use of support material or a multiaxis deposition head is required for complex three-dimensional geometry [4].

7- Sheet Lamination

Sheet lamination, a 3D printing technique, was one of the first to see widespread commercialization, but it has had only modest success thus far. Because of the cutting, stacking, and bonding steps that must be completed in a specific order, it is difficult to reuse the material that is left over after sheet lamination. When it comes to working with sheet material, however, it can be one of the most cost-effective and simple options. This method has proven to be useful when it comes to building large, heavy objects. Only a few industrial settings use sheet lamination at the moment [31].

3D Printing Technologies in the biomedical Field

The development of 3D printing has carried new hope to build the bio-mimic microenvironment [32]. Advantages from the 3D printing technologies, the usage of 3D printed biomimetic scaffold, 3D printed artificial tissue, and 3D printed lab-onchip are three main approaches to simulate the actual microenvironment.

3D printing allows the fabrication and design of biomimetic scaffold-based implants with more control and versatility [33]. Advanced 3D printing Produces novel biomimetic microarchitectures with adequate anisotropic properties [34]. In addition, 3D scaffolds can be fabricated with novel materials that sufficiently mimic the natural Extracellular matrix (ECM) by using a precisely developed printing process [34, 35, 36, 37]. The biomimetic scaffold can be used for tissue regeneration with the combination of different bioinspired materials and rapid prototyping techniques. Several novel bioinspired materials that facilitate the healing and regeneration of certain kinds of tissues have been suggested. For example, a novel bioinspired nanomaterial consisting of hydrothermally treated nano-crystalline hydroxyapatite (nHA) and core–shell polyacid (PLGA) was invented to mimic a constructive microenvironment for the regeneration of osteochondral tissue [38]. Due to the biomimetic structure and composition of nHA, the novel bioink provided mechanical strength for the fabrication of scaffolds by using 3D printing technology. Similarly, the Vivo experiment outcome suggested that such bioinspired nanomaterial improved human mesenchymal stem cell proliferation and osteochondral differentiation [35, 36, 37].

3D-printed lab-on-chip is a process that combines several microfluidic elements and techniques in a single chip to simulate chemical and biological functions [39, 40]. For example, microvascular networks are fabricated to create the lab-on-chip [41]. 3D-printed lab-on-chip is widely used for various objectives, including diagnosing diseases and biochemical analysis and detection [41]. The concept of lab-on-chip is conducting cell co-cultures in a dynamic fluid combined with controlled atmospheres contact to recreate significant disease models and understand the physiological mechanisms [42]. In lab-on-chip, the structure of the cells' living environment should be reconstructed to mimic the microenvironment. For example, the heart's muscle tissues forced the heart cells (cardiomyocytes) to couple mechanical stress to each other, and further generated elongated cell bundles, creating an anisotropic syncytium [43].

3D Printing Technologies in dentistry

3D printing technologies are playing increasingly important roles. A growing number of professional 3D printing companies for different dental treatments need medical equipment for professional, industrial production current applications of 3D Printing in the dental field include:

1- Advancements in Orthodontics

The capability for customized treatment and bio-mechanical planning offered by 3D imaging technology and innovations in computer hardware and software will be more completely realized in the coming decades. Combined with 3D Printing, these technologies have been used to customize equipment manufacturing, such as aligners and retainers [44]. three-dimensional force is an essential factor in determining tooth movement in orthodontic treatment. It is challenging to accurately estimate the force and torque on the teeth before treatment, resulting in accurate tooth movement. In orthodontic biomechanical systems, braces significantly impact periodontal tissue, including bone, teeth, and periodontal ligament (PDL). Using these three tissue simulation models is a critical step in measuring the force of the teeth with braces [45].

2- Rehabilitation of the Edentulous Arch

The technology of digital 3D images and computer design (including CAD, CBCT, and 3D Printing) has been enhanced, and these technologies have been incorporated with digital guided surgery [46]. Digital guided surgery has the possibility to be a precise and simplified surgical implant. also, these techniques can be used to minimize the need for surgery and prove less invasive than conventional implants. It also reduces the pain and healing period of the operation. Nevertheless, computer-guided surgery must still overcome anatomical barriers, especially in clinical cases where vertical and horizontal bone grafts are needed [47].

3- Dental Crown

Interim restorations are important for various factors including protecting pulpal and periodontal tissues, maintaining oral function and esthetics. In order to reach this goal, much attention must be paid to ensure the shape and suitability of such restorations. The healthiness of the restoration depends largely on the manufacturing process [48]. the techniques used to make temporary crowns, according to the manufacturing process, can be divided into direct and indirect methods. In the direct method, the temporary crown is directly manufactured on the prepared teeth, while in the other method, the temporary crown is cast on stone and then sent into the mouth . Yet, the drawback of the direct method that the heat released during resin polymerization in the direct method may lead to heat trauma to the dental pulp. Also, residual resin monomers may harm oral mucosa, leading to moss-like reactions or allergic stomatitis. in addition, the shrinkage of the resin due to the reduction of atomic distance in the low molecular weight monomers used. This contraction leads to discrepancies in size between the edges and the occlusion area. the crown's adaptation to teeth was improved with the help of indirect methods, the thermal and chemical risks of the teeth and mucous membranes were eliminated, as the aggregation process happened on the stones [49].

4- Removable Partial Denture Removable partial dentures (RPDs)

RPDs are applied to restore lost teeth and function. It is the only option for partially edentulous patients with financial restrictions or any other contraindication to fixed prostheses and implants. Traditionally, they are manufactured by using the lost-wax casting technique. The casting process takes time and effort and depends on the technician's skills. Rapid RPD manufacture is more possible with the development of oral scanning and 3D printing technology, which shows an acceptable fit and satisfactory clinical result [50]. Using 3D printing technology to restore teeth, function, and esthetics is full of obstacles because knowledge, skills, and technology are required. Despite advances in dental materials and technology, traditional cast partial dentures are still manufactured by waxen technology [51]. The required time, procedural errors, and multiple adjustments of the technician limit traditional wax loss techniques.

Limitation and challenges of 3D printing technology

Separation of the research and development of 3D printing technology from materials is not feasible; it is essential to consider the material characteristics. Nowadays, photocuring 3D printing has not yet made breakthroughs in these areas: (1) the smaller printing size of DLP, LCD technique ; (2) the longer printing time and lower conversion degree because the light intensity of LCD is weak (3) the printing size of SLA technique is large, but the printing efficiency is low; (4) photocuring 3D printing resin with high viscosity; (5) there is no standard of the photocuring 3D printing technique; significant improvement will be made in photocuring 3D printing technology, If the above problems can be solved, which will enlarge the application of photocuring 3D printing [52].

Personalized manufacturing is best achieved through 3D printing technology, which matches the characteristic of biological tissue. The high printing precision and high speed of Photopolymerization 3D printing will have an outstanding application opportunity in biological tissue. Yet, the biocompatibility of materials is very important for biomaterials. Hence, it is essential to produce biocompatible materials for photopolymerization 3D printing [53].

The future of 4D printing

4D printing is a new vision, and few technologies are suitable for printing adaptable objects [54]. Poly-Jet (Stratasys Ltd) is utilized to produce multi-material objects and is based on depositing curable liquid photopolymers layer-by-layer. Selective laser melting (SLM Solutions) is used for constructing metallic components. Newly, direct-write printing (DW) is a technology suitable for printing polymeric solutions that have been developed to enable 4D printing for biomedical applications [55, 56]. Also, there is no inquiry that new concepts of 4D printers should be expanded or that existing 3D technologies should be enhanced in the foreseeable future. This should be followed in parallel with the improvement of the materials [57].

Summary

An ink printer layers liquid ink on paper to create images, whereas a 3D printer layers molten plastics (or other materials) on top of each other to create three-dimensional objects. A 3D printed part, like any machined part, will be produced most efficiently if it is designed with CAD. 3D printers follow the instructions contained in the CAD model. They use this data to determine how much material to deposit and where to deposit it.

Engineers must occasionally return after a part has been printed to machine the part. This is due to 3D printing's inability to produce parts with tight tolerances on a regular basis.

For example, 3D printed parts for the medical and aerospace industries are frequently not functional or safe right away. Parts like this must be returned to a CAD program for further modeling at the specified scale before being exported to a CAM program to be programmed for the machining aspect. Machining is typically fast, with a focus on finishing toolpaths that produce high-quality surface finishes.

The primary difference between CAD/CAM and 3D printing is that 3D printing is a component manufacturing process, whereas CAD/CAM is the process of designing and manufacturing these components.

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