3D PRINTING AND DIGITAL WORKFLOW IN IMPLANT DENTISTRY: CURRENT APPLICATIONS AND FUTURE DIRECTIONS

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ABSTRACT

3D printing and digital workflows have transformed implant dentistry, with improvements in both accuracy, personalization, and efficiency of the treatment planning and execution processes. Within this short review, the current applications of 3D printing technologies will be considered, including the fabrication of surgical guides, customized abutments, and provisional restorations. Different printing techniques, which offer the potential for either numerous benefits or drawbacks, will also be discussed. While 3D printing presents considerable benefits, including minimization of turnaround times and the possibility of achieving same-day restorations, material compatibility, equipment costs, and requirement for experienced operators are still some of the issues that remain before its full exploitation. Comparative studies have demonstrated superior internal fit and mechanical properties of restorations printed by 3D printer technology with respect to classical CAD/CAM systems in clinic, which underlines relevance. The application of materials in dental 3D printing, from bioceramics to advanced thermoplastics, contributes to the development of prosthetics that are best in terms of mechanical strength as well as biocompatibility. Looking ahead, the advancements that are available with better planning algorithms and intraoperative printing will contribute further to the care of patients. This review emphasizes the promise that 3D printing, and digital workflows hold for revolutionary changes in implant dentistry as a lead-in to bespoke, time-saving, and effective clinical procedures focused on patient satisfaction

INTRODUCTION

Digitization of the workflows and processes related to 3D printing transformed implant dentistry with unprecedented accuracy, customization, and efficiency in treatment planning and execution.[1,2] Transition from conventional to CAD/CAM systems revolutionized restorative dentistry in general and, in particular, dental prostheses production - implants, crowns, and bridges. CAD/CAM systems ensure very precise, patient-specific restorations, and the clinical outcomes are excellent. [3]

The same reasons of rapid prototyping and same-day restorations have changed the production of dental structures. Its application areas include the productions of surgical guides, customized abutments, and provisional restorations. [4] This technology also supports easier preoperative planning with diminished potential complications. Moreover, the possibility of processing various biomaterials such as ceramics, metals, and polymers offer extensive treatment options and caters to the increasing interest in personalized treatments.[5]

Though 3D printing has many advantages, there are a few challenges, like material compatibility, high costs of the equipment, and the necessity of skilled operators to use the equipment.[5,6] The purpose of this review is to discuss current applications of 3D printing within the framework of digital workflows in implant dentistry, examine benefits and limitations of these technologies, and discuss future directions for clinical practice and research.

GENERAL OVERVIEW OF 3D PRINTING TECHNIQUES, ADVANTAGES, AND DISADVANTAGES

Three-dimensional printing was first developed in 1993 at MIT, and it has revolutionized dentistry, especially in cases involving implant procedures.[7] It enhances customized prosthetics with various techniques, including stereolithography, selective laser sintering, and digital light processing, faster and more accurately manufactured.

3D Printing Techniques in Dentistry

The most commonly used 3D printing techniques in dentistry are divided into broad categories, namely extrusion-based, sintering, lithography-based, and powder binder technologies.[7] These methods differ in the type of materials involved, level of detail that can be reached, and the characteristics of the end products fabricated.

a. Extrusion-Based Methods

Fused Deposition Modelling (FDM) is an extrusion-based 3D printing technique that employs the melting of thermoplastic materials to model prosthetics. Although cost-effective and user-friendly, it has some limitations such as poor resolution and surface finish necessary for intricate prosthetics.[8] Recent advancements include the integration of microfluidic systems to achieve a new dimension of precision in dental applications.

b. Sintering-Based Processes

Selective Laser Sintering (SLS) and Selective Laser Melting (SLM) use high-power lasers to fuse various powdered materials, including metals and ceramics, to create durable dental prosthetics. However, they are costly and require additional processing for improved surface quality.[9]

c. Lithography-Based Methods

Photopolymer resins used in SLA and DLP 3D printing are cured by lasers or light sources. SLA offers high accuracy for dental prosthetics, while DLP provides resolution but faces shrinkage issues. Hybrid techniques combine SLA and FDM for improved results. [9]

d. Powder Binder Methods

A technique called powder binder printing by which a layer of a powder is printed layer by layer utilizing a solution of a binder. Calcium phosphate powders, recently developed in the field of dental tissue engineering, can simulate natural dental tissues and improve implant applications, but long-term in vivo biocompatibility requires further studies. [10]

Advantages of 3D Printing in Implant Dentistry

The integration of 3D printing in implant dentistry provides important advantages over traditional techniques. It facilitates the creation of patient-specific prosthetics without the possibility of an error, especially in complicated cases. There is also a significant reduction in the turnaround time, enabling same-day treatments, which makes patients feel much better and have very good outcomes.[10,11] Although the investment is huge at first, the savings in the long

run are substantial because of material waste reductions and the ability to make several prosthetics at once, thus making it more cost-effective.

Disadvantages of 3D Printing in Implant Dentistry

Although 3D printing in implant dentistry has advantages, it has its drawbacks; one of them is limited material options, especially regarding long-term durability and aesthetics. Most prosthetics require some intense post-processing, such as cleaning and polishing, which will increase production time and inaccuracies. [11] It also has a high initial cost for 3D printing equipment, discouraging small dental practices, although savings on materials and time might become beneficial in the long run. [12]

APPLICATION OF 3D PRINTING IN DENTAL PROSTHESES

For the first time, revolution technique of 3D printing is in use in the field of dentistry, especially for provisional dental restorations like crowns and bridges. Though this technology is of a recent nature, entering clinical settings only through some studies started in 2013, it has already drawn attention towards its innovative role in elevating the standards and efficacy of dental restorations.[13]

Marginal and Internal Fit

For the long-term survival of 3D-printed restorations, fit is considered as the critical factor for both functional and aesthetic outcomes. Marginal and internal fit have been described as significant factors influencing the longevity of dental restorations. [13,14] Various parameters are associated that could affect the marginal fit of the prosthesis produced using 3D printing by resins, specifications of printing machine, calibration of the machine, and complexity of design of the restoration. [14]

Recently, many studies have compared characteristics of 3D printed restorations with those produced with conventional techniques systemically, highlighting strengths and weaknesses of each method.

Comparative Research

Recently, the advantages of 3D printing in dental restorations have been revealed. Lee et al. showed that the 3D printed crowns had an excellent internal adaptation with a mean discrepancy of 141.1 µm and 91.1 µm, while the CAD/CAM milling systems had a mean discrepancy of 171.6 µm. Tahayeri et al. optimized the low-cost stereolithography 3D-printed bridges and crowns; in the 3D-printed samples, greater peak stress levels were observed compared to conventionally cured samples, suggesting a potential improvement in performance. [15] Alharbi et al. and Chaturvedi et al. have reported that with various finishing line designs, 3D printed restorations exhibited smaller internal gaps and improved marginal fit than their milled counterparts. [16] However, Zimmermann et al. proved that the 3D printing materials have similar fracture loads as the best results of CAD/CAM materials, therefore ensuring appropriate mechanical properties for use in the application area of dental restoration. [17] In short, it is evident that 3D printing affords excellent benefits regarding fit and mechanical properties in dental restorations.

Practical Uses and Inventions

3D printing also plays a significant role in creating surgical guides for dental implants, allowing for precise positioning based on digitally captured models of a patient's jaw and teeth. The process typically involves obtaining a digital scan, designing the surgical guide using specialized software, and fabricating the guide through 3D printing. [18, 19] This approach not only improves surgical accuracy but also enhances the overall treatment experience for patients.

DENTAL 3D PRINTING MATERIALS

The technique for 3D printing has made the best possible accuracy for creating prosthetic cases that are tailored precisely. Some techniques have emerged and use hydrogels, ceramics, metals, resins, and thermoplastic polymers. In particular, ABS, PLA, and commercial resins have

extensively been used for dental prosthetics, mainly for good mechanical properties and biocompatibility. [20, 21]

New innovations reflect the development of bioceramic materials with the highest level of biocompatibility and mechanical strength they need for dental application. Zirconia, alumina, and hydroxyapatite already exhibit the characteristics of durability and resistance to wear properties to qualify them as excellent candidates for use in stress-bearing restorations. [21] Composite materials have also been used for the combination of ceramics with plastics or metals to be used to increase aesthetic appeal and functionality in dental prosthetics. [22]

Thermoplastic polymers, particularly polyethylene (PE), polypropylene (PP), and PLA, are applied extensively for 3D printing purposes because of their ease of processing and good characteristics. Photopolymerization is one of the better techniques used because it provides a better finish and mechanical strength. Recent studies have shown that some advanced thermoplastics, like PMMA and PEEK, are ideal due to their excellent thermal stability and durability properties. [22,23]

Although various challenges are accompanying ceramic and metal printing, novel approaches such as selective laser sintering (SLS) contribute a lot to the overcoming of these challenges. In the case of 3D-printed dental materials, advanced manufacturing techniques will serve to make better mechanics along with function, unlocking greater future developments in implant dentistry.

PROSPECTIVE DIRECTIONS AND CONCLUSION

This integration of 3D printing and digital workflows in dental implantation marks a paradigm shift in undertaking personally tailored patient care and increased procedural efficiency. [24] Such advanced technology can provide highly customized implants and prosthetics about individual anatomical specifications, thereby further elevating the surgical outcomes and primarily the level of patient satisfaction. Applications range from surgical guides to temporary crowns and definitive restorations, representing the possibility of drastically reducing turnaround times with the utmost accuracy levels. [25]

Future developments include the application of materials to enhance osseointegration and even more sophisticated software algorithms in support of planning and simulation. [26] Beyond these opportunities lies the possibility that real-time intraoperative 3D printing will literally rewrite the rules of the game with respect to the placement of implants because it enables immediate customization and the ability to make on-the-spot adjustments during surgery. Further research will address further challenges including material limitations and the need for robust quality assurance processes. In conclusion, the potential blending of 3D printing with digital workflows in the field of implant dentistry promises revolutionizing impact as it signals a new age of maximized accuracy, efficiency, and patient-centered care in the art and science of dentistry.

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