APPLICATIONS OF 3D PRINTING IN ORAL AND MAXILLOFACIAL SURGERY

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ABSTRACT

INTRODUCTION: Three-dimensional (3D) printing, also known as "rapid prototyping" or "additive technology" is a manufacturing process that has undergone significant development during its 40-year history.

AIM: The aim of this review is to analyze and summarize the applications and advantages of 3D printed models in contemporary oral and maxillofacial surgery.

MATERIALS AND METHODS: PubMed, Medline, and Google Scholar databases were searched in order to select articles related to the topic. The review includes fifty-four articles written in English language, published from 1980 to 2022.

RESULTS: 3D printed models can reproduce cone-beam computed tomography (CBCT) scans of hard tissues extremely accurately. The possibilities for a personalized approach, virtual planning of the operation, surgical navigation, and the ability for individualization of implants have been established as reliable means in maxillofacial traumatology, implantology, and orthognathic surgery.

CONCLUSION: The implementation of three-dimensional printing technology in the oral and maxillofacial surgery (OMFS) practice enhances accuracy, predictability and precision, while simultaneously reducing time and costs, respectively increasing the benefits for the patient.

Keywords: *3D printing, medical rapid prototyping, preoperative planning, surgical simulation*

INTRODUCTION

Three-dimensional (3D) printing, also known as "rapid prototyping" or "additive technology" is a manufacturing process that has undergone significant development during its 40-year history.

In 1986 Charles Hull presented the first three-dimensional printing technology by patenting stereolithography (SLA) and developing a 3D printing system. Since then, 3D printing has been constantly evolving.

At present, additive technologies are applied in multiple fields, such as automotive production, space engineering, and medicine.

Among the biggest advantages of additive technology is the ability to create almost all kinds of complex geometric forms in an entirely automatized manner, as well as the speed of their production, compared to conventional subtraction technologies.

Today, this technology is gaining attention and popularity, focusing especially on applications related to oral and maxillofacial surgery (1).

The integration of 3D printing in different fields of dentistry has enabled the production of complex surgical, orthodontic and prosthetic appli-

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ances, which fulfill the high requirements for resistance and flexibility in these fields.

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RESULTS

Alberti is probably the first scientist who recognized the opportunity to obtain 3D models from computed tomography (CT) images (2). Over the years, this process has evolved and progressed so much that now it is possible to rapidly prototype models from computed tomography (CT) and cone-beam computed tomography (CBCT) scans, as well as magnetic resonance imaging (MRI), or even ultrasound examinations (3).

Medical rapid prototyping (MRP) has gained wider popularity in medicine due to the cost reduction for the production of these models. Besides maxillofacial surgery, 3D models are applied in neurosurgery, orthopedics, cardiology, plastic surgery, otorhinolaryngology (4,5). They assist the surgeon in the planning of the intervention, its explanation and presentation to the patient, and serve as guides, which considerably reduces the intraoperative time (6,7).

Medical rapid prototyping is defined as the production of spatially accurate physical models, replicating anatomical parts of the human body (4). Common sources of information for their production are CT and CBCT scanned images.

The acquired DICOM files, with the aid of specialized computer-aided design (CAD) software, are converted to Standard Tessellation Language (STL) files. Consequently, these STL files are transferred into a 3D printer, where the process of rapid prototyping (or broadly speaking 3D printing) essentially starts (3).

These previous steps require major expertise and understanding of medical imaging. The construction of reliable, dimensionally accurate models necessitates a team of specialists in medical imaging, surgeons, and engineers (8).

Three-dimensional printing technology includes fused deposition modeling (FDM), selective laser sintering (SLS), stereolithography, selective laser melting (SLM), polyjet printing (PJP), and bioprinting (9,10,11).

A variety of materials can be used, such as metal powder, eutectic metals, metal alloys, photopolymers, thermoplastics, ceramic powder, paper, plastic film and living cells (12).

The technologies for the fabrication of 3D models were developed as early as the end of the 1980s, but due to high production costs, they were applied only for solving complex cases. With their advancement and progress, however, they have become more widely available. The technological advances in the methods for radiological examination, as well as the three-dimensional processing of the acquired data, have clearly outlined the role of 3D technology in favor of doctors and patients.

A study by Winder and Bibb defined the main benefits of using individually produced anatomical models. Among them are planning and placement of implants in the maxillofacial region, improving the preoperative preparation and treatment planning, as surgical guides. Additionally, they point out the role of 3D models for diagnosing and determining the extent of tumors, congenital anomalies and deformations, post-traumatic impairments, and maxillofacial diseases (4).

Petzold et al. used over 200 3D models in the treatment of different diseases in the maxillofacial region, with an objective to optimize the planning and execution of the surgical intervention. As a result, they concluded that the presence of a three-dimensional anatomical model allows for preliminary training for the execution of the intervention, practicing different types of surgical access, as well as utilization of the standard surgical armamentarium. Hence, the advantages of this technology repeatedly exceed the data provided by three-dimensional radiography (13).

At present, 3D printed models extremely accurately reproduce CBCT scans of hard tissues, but in the region of the dentition, artefacts can often be seen. They are most frequently caused by the presence of metal restorations, orthodontic appliances, dental implants (14).

The possibilities for a personalized approach, virtual planning of the operation, surgical navigation, and the ability for individualization of implants have been established as reliable means in implantology, orthognathic surgery, and maxillofacial traumatology.

The implementation of these technologies enhances accuracy, predictability, and precision, while simultaneously reducing time and costs, respectively increasing the benefits for the patient (15).

Despite the fact that CBCT provides adequate information to the clinician, 3D printed models allow for direct physical observation of anatomical structures and enable the execution of a presurgical simulation of the procedure (16). The simulation over the individualized three-dimensional model of the patient ensures its straightforward and uncomplicated implementation in person, which in turn leads to superior and more predictable results.

Furthermore, the application of a 3D printed educational and training model is preferable to using materials from cadavers, because it offers conditions maximally resembling the actual clinical environment, an unlimited number of models, and financial accessibility (17).

Applications of 3D Printing Technology in Preoperative Treatment Planning and Simulation in Oral and Maxillofacial Surgery (OMFS)

One of the first applications of 3D printing in surgery is related to the production of anatomical study models (18). This technology has become more accessible with the mass exploitation of another contemporary technology, namely CBCT (19,20). Cone-beam computed tomography has changed the diagnostics and treatment planning in modern oral surgery, dental implantology, and endodontics (21,22).

Preoperative transferring of information from CBCT to a 3D printer and obtaining a detailed replica of the jaw allows for a thorough and diligent assessment of the individual anatomic setting, as well as planning of the surgical access (23).

With the incorporation of the technology for rapid prototyping of digital images, medical anatomical models have found an even wider application as means for surgical planning. They permit preoperative simulation virtually, as well as materially, in the form of a 3D printed model. The information provided by CBCT allows for the production of these 3D models by utilization of 3D rapid printing machines.

3D models printed this way enable the surgeon to review and assess all anatomical structures and gather a more genuine idea for the expected clinical situation. In addition, such models allow for the preliminary fabrication and adaptation of different bone plates, orthodontic appliances, etc.

The introduction of this new technology in the clinical practice could substantially supplement and enhance the quality of the standard methods for preoperative planning, as well as reduce intraoperative time. Moreover, printed models are an appropriate means for education, as well as visualization, in conjunction with elaboration to the patient regarding the upcoming intervention and receiving the patient's consent before performing the surgery (24).

Somji et al. used a 3D printed model of the upper jaw, obtained by CBCT, with an objective to perform thorough preoperative diagnostics, prepare a treatment plan and carry out a presurgical simulation of the procedure of maxillary sinus augmentation via lateral window approach. Thanks to the model, they precisely planned the design of the flap, the size and location of the anthrotomy, as well as assessed the location of the posterior superior alveolar artery and the thickness of the Schneiderian membrane. In conclusion, they identified the integration of a 3D printed model in the planning of the complex augmentation procedure as a substantial advantage, compared to its planning by using only the data from CBCT. Furthermore, they pointed out that applying the method is lowering the risk of intraoperative complications related to tearing the sinus membrane or hitting a blood vessel, as well as reducing intraoperative time (25).

Applications of 3D Printing Technology in Maxillofacial Fracture Treatment

Patients with trauma in the maxillofacial region represent a challenge for the surgeon, considering several factors: poor visual control due to the presence of overlapping soft tissues; difficult access to deep skeletal structures; potentially compromised postoperative results due to improperly adapted fixators. Intraoperative inaccuracies often have a cumulative effect, resulting in facial asymmetry, malocclusion, diplopia.

The integration of 3D printing in the practice has considerably affected the work of clinicians, as well as the patients. It allows for not only the enhancement of the preoperative assessment and treatment planning but also the preliminary fabrication of individualized appliances for the fixation of the fragments (26). This can shorten the operative time by up to 20% thanks to which the percentage of postoperative complications is also reduced (27,28).

Dessoky et al. used individually fabricated polyetheretherketone (PEEK) plates for the fixation of mandibular fractures in 10 patients. The results of their study show that the preliminary adjusted plates are distinctly accurate to the operative field, which reduces intraoperative time. A six-month follow-up of the patients displays satisfactory clinical and radiographic results (29).

Individually fabricated appliances demonstrate high precision and adaptability to clinical situations, resulting in improvement of the esthetics of the patient, owing to the correct restoration of symmetry of the facial contours (24). Replication of the unaffected contralateral side considerably improves the accuracy of the reconstruction (30).

Patel et al. reconstructed a residual defect in the fronto-orbiral region and a dislocated zygomaticomaxillary complex. By using the data from the patient's CT they made a three-dimensional PEEK implant, which they fixated in place of the acquired defect, restoring it esthetically and functionally (31).

Applications in Cranio-Maxillofacial Reconstructions

Computer-aided design–computer-aided manufacturing (CAD-CAM) was first introduced to fabricate craniofacial anatomical models based on images from CT in 1987 (32).

Skull bones have irregular outlines, which leads to difficulties in standardizing cranial implants. Medical rapid prototyping models are beneficial for recognizing the ideal donor site for grafting. For example, reconstruction of the skull can be accomplished using a split calvarial bone graft and the ideal donor area can be accurately located in advance (33).

3D titanium-based implants can be useful for reconstructive calvarium and maxilla surgery. The precise preoperative simulation provides customized resection guides, as well as excellent fit and design of the implant (34,35).

The reconstruction of the mandible after extensive resection of tumors can be very challenging. Alteration in the alignment of the mandibular structures can negatively affect not only the esthetics but also the function due to malocclusion (36). 3D printed MRP models were developed and used to prebend titanium reconstruction plates. This technique allowed the accurate adaptation of the plates, undergoing minimal handling during the operation and reducing operating time considerably. As a result, it was easier to accomplish excellent mandibular symmetry (37).

Applications in Implant Treatment Planning

According to recommendations, provided by the American Academy of Oral and Maxillofacial Radiology (AAOMR), "The goal of presurgical dental implant treatment planning is to position the optimum number and size of implants for the best restorative results. This can only be done if the location and axial angulations of each implant are determined by a thorough knowledge of the patient's bony anatomy is provided in a complete radiographic examination that includes the third dimension" (38).

Nowadays implant surgical guides and anatomic models are made using CAM software. Images obtained from CT and CBCT are transferred to a computer in order to plan the surgical guide. 3D models made of acrylic resin and surgical guides are then printed. Once hardened, the guides contain spaces for stainless steel drill-guiding tubes. Metal cylinders are then glued into the spaces, and the guides are ready to be used clinically (39). These bur-guiding cylinders allow for accurate drilling and implant placement, which gives good results for the patient and the clinician. The implant can be placed in the position, angulation, and depth by merging the digital data of the bone with planned restoration. A provisional or permanent restoration can then be fabricated preoperatively on the cast. The outcomes of this procedure are precise and predictable, as well as the final restoration (40).

Applications in Orthognathic Surgery

3D printing technology allows preoperative fabrication of personalized orthognathic surgical guides. This allows accurate implementation of the osteotomies, positioning of bone segments, drill holes and screws, ensuring the right placement of bone segments (41).

Three-dimensional printed models have been widely used for distraction osteogenesis planning (42), correcting craniosynostosis (43), genioplasties (44).

Applications in temporomandibular joint (TMJ) Reconstructions

Temporomandibular joint pathologies that involve the condyle and the ramus of the mandible require joint resection, followed by a total joint prosthesis (45). 3D printed prostheses, composed of various combinations of materials, replicating the original anatomy, can successfully restore anatomical structures and function, providing reliable treatment outcomes (46).

Fabrication of Tissue-Engineered Scaffolds

3D printing technology has evolved to bio-cell printing for the creation of 3D scaffolds for tissue engineering (11).

These innovative methods have been gaining popularity in experimental approaches such as bone grafting in reconstructive surgery. 3D printed bone scaffolds have the potential to replace autografts and allografts because of their advantages, including unlimited supply and the ability to tailor the scaffold's biochemical, biological, and biophysical properties (47).

Using this technology, reconstruction of fractures or other bone deficient areas can be accomplished. These scaffolds can be used to generate hard and soft tissue, using biocompatible materials. They can be accurately fabricated according to the required shape and dimensions, predesigned by 3D planning.

Another advantage is the possibility to add osteoinductive factors, like bone morphogenic proteins, to stimulate osteogenic differentiation, which increases the integration between the printed scaffold and the recipient site (48).

Three-dimensional printed cell cultures were also used for experimental tissue engineering to produce artificial tissue in vitro models (49). They aided in the formation of human bone and skin grafts in vitro (50).

DISCUSSION

3D printed models and appliances have several purposes in the medical setting and are broadly used in contemporary surgery. Studies of maxillofacial and cranial fractures have reported enhanced results due to the use of anatomical models as guides prior to and during surgery, in order to understand the pathology better and to avoid complications (26–29).

These anatomical models are also often used to shape implants prior to the surgery, resulting in an improved fit of the implant, therefore improved clinical and esthetic outcomes and reduced operation time (51,52).

In maxillofacial surgery, 3D printed models and surgical guides are increasingly used for mandibular reconstructions and orthognathic surgery (53).

Patients can additionally benefit from this technology, as anatomical models improve their understanding of the pathology and the upcoming procedure. This results in better patient-doctor communication and greater patient satisfaction (15).

Still, some authors question the routine use of dental guides because of the associated higher costs and suggest that they should be used only for solving complex cases (54).

Thus far, there are no publications mentioning decreased medical outcomes due to the use of 3D printed models or appliances.

CONCLUSION

3D printed models present possibilities for a personalized approach, virtual planning of the operation, surgical navigation and implant individualization. The implementation of this technology in the OMFS practice enhances accuracy, predictability and precision, while simultaneously reducing time and costs, respectively increasing the benefits for the patient.

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