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Grado en Odontología

APPLICATIONS OF 3D PRINTER IN DENTISTRY

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Abstract

Objectives:

1.Discuss the 3D printing applications in different specialization of dentistry.

2. Discuss materials properties used for 3D printing applications in dentistry.

3. To explore the future of 3D printing applications in dentistry.

Methods:

Scientific data bases of Google Scholar, Medline, PubMed and UEM CRAI library were used to attain the scientific articles need which were related to the topic of applications of 3D printer in dentistry.

Conclusion:

The role of 3D printing in dentistry was still conservative and auxiliary, the development for further involvement in dental treatment would rely on more advanced materials and printing methods that could demonstrate more characteristics and could compete with traditional methods and materials. Following the success of CAD/CAM system and digital oral imaging technique, the benefit of 3D printing applications would be endless, alongside with more education and promotion, the acceptance of the technology would bring more options for clinician because the main goal of the clinician was always to maximize patient’s benefit.

Keywords:

3D printing in dentistry, Stereolithography, Digital light processing, Photopolymer jetting, Fused deposition modeling

Resumen

Objetivos:

1. Discutir las aplicaciones de la impresión 3D en diferentes especializaciones de la odontología.

2. Analice las propiedades de los materiales utilizados para las aplicaciones de impresión 3D en odontología.

3. Explorar el futuro de las aplicaciones de impresión 3D en odontología.

Métodos:

Se utilizaron bases de datos científicas de Google Scholar, Medline, PubMed y biblioteca UEM CRAI para alcanzar la necesidad de artículos científicos relacionados con el tema de las aplicaciones de la impresora 3D en odontología.

Conclusiones:

El papel de la impresión 3D en odontología todavía era conservador y auxiliar, el desarrollo para una mayor participación en el tratamiento dental se basaría en materiales y métodos de impresión más avanzados que podrían demostrar más características y podrían competir con los métodos y materiales tradicionales. Tras el éxito del sistema CAD / CAM y la técnica de imágenes orales digitales, el beneficio de las aplicaciones de impresión 3D sería infinito, junto con más educación y promoción, la aceptación de la tecnología traería más opciones para el médico porque el objetivo principal del médico era siempre para maximizar el beneficio del paciente.

Palabras clave: Impresión 3D en odontología, estereolitografía, procesamiento de luz digital, inyección de fotopolímero, modelado por fused deposition

INDEX

1. Introduction

The Rapid development of 3-Dimensional (3D) printing speeded up the technological advancement of model manufacturing, expanding the applications towards different industries and providing multiple options to resolve complex situations. As dentistry approaching to be more digital than ever, the integration of 3D printing and more digital process are demonstrating further capability to provide alternative treatment options. The material and manufacturing advancement altered the treatment approach and logistic of dentistry, expanding the scope for different specialties. 3D printing can be a modern approach for a quick and highly tailor-made production for dental appliances and models, combining with the oral digital imaging technique, benefits not only the dentist and the technician and patient too. The advantages of the combination of the printing and imaging technique influence from the diagnosis stage to post treatment outcome; hence, 3D printing can be utilized in all stages within a dental treatment. Basing on the technology of the 3D printing technique, the involvement of other techniques is required, for example, oral imaging technique, Computer aided design and manufacture (CAD/CAM) which are immensely popular tools in dentistry and has been widely used for making dental crowns, cast models and even orthodontic appliances. With that said, this article will further explain the theory behind 3D printing and the applications in dentistry, also how the printing technology incorporate with day-to-day dentistry procedures.

The principles of 3D printing will allow further understanding of how 3D printing can be implemented into dentistry. 3D printing can be defined as printing method of additive manufacturing or layering manufacturing. The printing process involves creating a 3D object with multiple layers of materials stacking up together. However, to construct the object in multiple dimensions, a digital virtual design must be made previously for the printer to fabricate the object, the design made will be dissect into numerous thin layers, then will fabricated layer by layer to produce the shape and structure. Depending on the system or brand type, all 3D printing requires a digital format to execute the production, once the digital file is obtained, then the printing process is straight forward, adding all the 2-Dimensional (2D) layers to create the 3D object. Hence the name Additive manufacturing.

With the current trend of 3D printing, there are a few different printing techniques that vary in materials of fabrication and modalities.

The existence of various technology can be applied to different applications in dentistry, each carrying strengths and weaknesses, However, most techniques share a common problem of high cost and production value, which limits the usage of such devices. Also, the maintenance and post-production procedures can be complicated. With that said, only a few printing techniques were introduced into dentistry and a selection of applications were developed. In dental application, current printing techniques can be divided based on the material used to fabricate the model such as light cured resin, thermoplastic, and others such as powder binding and sintered powder.(1)

Light cured resin can be found in techniques such as stereolithography, photo-jetting and digital light processing which these three techniques are relatively high cost and requires a supporting structure in the printing process which will be explained further on. And alternative material option is the thermoplastic which is used in fused deposition modeling (FDM) which does not involve any photo polymerization process. This article will elaborate on the applications of 3D printing in dentistry, different techniques, and examples of the applications.(2)

Stereolithography (SLA)

Stereolithography was first introduced in the 1970s by the Japanese scientist Dr. Hideo Kodama with the technology of UV light curing the photosensitive resin then the technology was rapidly developed during the 2000s and hence now small size and domestic 3D printing is available. (3)Stereolithography is commonly known as resin 3D printing due to its characteristics of printing which involves a light source, normally a laser then the laser cures the light reactive thermoset resin into hardened models, different variations of this technique lie in the arrangement of the main components of this printing method, such as the light source, the resin material used, the building platform as well. The mechanism of the hardening of the resin is basically the laser or light source carries a certain wavelength that will promote the short molecular chains to join and creating a solid and hard geometries. The layer of resin material is printed out or constructed with the building platform descending whilst the hardening process begins on the upper part of the structure, hence the model that is printed out is normally upside down, with such method a supporting structure will be needed to maintain the shape of the model which is used during printing and will be removed later when the final model is made. Also, for final stages, the model will be put into an UV oven to make sure polymerization of the resin is completed.(1,2)

Digital Light processing (DLP)

Digital light processing shares similarities to stereolithography because both are creating the 3D model layer by layer with light cured or photo polymerized resin, the difference lies between the light source used to polymerize the resin. SLA uses ultraviolet light to create the cross-sectional layers like drawing out the layer step by step whilst DLP uses a digital light projector to project the cross-sectional layer all at once.(1)

Photopolymer jetting

Photopolymer or material jetting are an additive manufacturing process that is like a normal inkjet printer that can be found in homes and offices in regarding the printing a 2D layer method. The reason why the jetting process is similar to an inkjet printer is because the material or photopolymer will be ejected from a printhead then with the help of ultraviolet light or any other energy light source to solidify the polymer, then once a 2D layer is created, the second layer will be printed on top of the original layer to create a 3D model, building the 3D shape in multiple layers. Normally, the material used is liquid form of thermoset photopolymer to allow the printhead to eject the material in the desired pattern or according to the design of the digital format, the material will first be heated up in a reservoir to obtain the ideal viscosity for the printhead to print, then the printhead will travel in a 2D plane position to create the layer, as the printhead is traveling ejecting the material, there will be an light source, ideally Ultra violet light attached to the printhead to help polymerize the liquid immediately as the printing process goes. After one layer is completed, the platform carrying the model or layer will descend to allow the next layer to be print on top.(1,2)

Due to the special dispensing method of the material, material jetting allows multi-material printing, colorized printing and multiple printhead can be used at the same time to create a layer or model. The multi-material printing allows the use of a range of materials such as resin, rubberlike or hard plastic texture materials to create a different application in dentistry. The multiple printhead system allows the printing of different texture or properties in the same model.

However, the drawback with such manufacturing process is that the model that is printed will require a supporting structure during the process to maintain the shape and integrity of the 3D model which later will be removed. The supporting structure can sometimes be difficult to remove after the completion of the structure and damaging the original model when the model is complex.

The difference between stereolithography and material jetting is that material jetting does not require a post print photopolymerized process due to the instant curing when the material is ejected out the print head.

Fused deposition modeling (FDP)

Fused deposition modeling is an additive manufacturing technique that involves the mechanism of a material which will be heated to a molten stat while ejecting through a nozzle to create the model layer by layer, the movement of the nozzle will be guided by the digital design file. The initial purpose of fused deposition modeling is for fabrication of prototype and model making that required rapid printing and alongside the advantages of minimizing the waste of material for print and allowing the printing of complex structural designs. These characteristics lead to the plebeianize of the 3D printing, with that said, desktop printers became a popular domestic option for hobbyist and companies that want to minimize the cost of printing.

The fused deposition modeling utilizes thermoplastics that can be found in a lot of desktop printers, normally the thermoplastic will be in the form of a filament feeding into the nozzle with the help of a pinch roller that sustain the outflow of the ejection of the material out of the nozzle. The nozzle will contain a heating source or thermal module that will create the liquid or molten state of the filament then ejecting the material down to a platform creating the layer. The nozzle will be traveling in horizontal axis laying the material layer by layer to make a 3D model. When the material is ejected, the bonding and cooling will start simultaneously, bonding will be directed towards the adhesion of the previous bottom layer and cooling due to the thermo sensitive characteristics. The model will then harden due to the temperature change hence maintaining the structural integrity, saving time in the process without the polymerizing protocol.(1)

The model outcome of fused deposition modeling is always compared with other techniques because the finishing of the surface of model presents difference that might result in accuracy problems which can be explained by a few factors of the nozzle, such as the diameter of the ejecting component, the filament feeding rate, the ejection rate of the material and the thermoplastic properties. And the integral strength of the model because the cooling time of the material and filament type can affect the bonding of each layer.

The dental industry has been undergoing changes digitally in treatment protocols and materials, not only in specialties but also in dental lab work. The digitalization of dentistry provided multiple functions, such as better pretreatment evaluation/ prediction in terms of aesthetic and functional purposes, improved accuracy for functional appliances planning and fitting and computerized aiding in design and manufacturing. Different specializations are adopting the digital workflow and showing promising improvements, the advantage of digital technology is that the flexibility to incorporate into traditional treatment planning and protocol. It can be added into different stages of the treatment. From the treatment planning stages, to presenting treatment outcome and aiding treatment process and actual prosthetic treatments. Hence, 3D printing technology can be incorporated into the traditional workflow without any interferences. The 3D printing technology involves more digital rendering protocol since the printing machine requires a digital file input to follow and print out the model. With traditional dentistry, alginate or silicone impression are used to record the patients' oral condition and converting into a cast model for further analysis and lab work communications, with advance digitalization in dentistry oral scanning imaging technology has emerged and has been implementing in different sectors of dentistry.(2)

The workflow of dentistry can vary from different specialization but the basics of obtaining information from the patient's oral cavity has always been the same. Physical impressions were widely used since the start and played key role in dentistry. Using alginate and silicone to duplicate the patient's oral information are still being taught in dental schools all around the world and still the most popular and economical option that is in the market. Followed by the plaster model making and mounting it on articulators, the recreation of a patient's oral cavity can be done within an hour, then analyzation can be done and send away for lab works.
The traditional method is a physical and 3D option for oral data analyzation. However, during the process, human and material errors can affect the accuracy of the recreation of data outside of the patient's oral cavity. For example, alginate impression taking techniques, the quality of the alginate, transferring data to articulator, logistic of the cast model, type of plaster used and so on. These factors are accounted for when taking accuracy into consideration. Furthermore,

traditionally models of patients are delivered to laboratories allowing the technicians to work on and return to the dental clinic. The logistics of such protocol can also increase the risk of error and delays in a dental treatment and most importantly time consuming. Even with the sophisticated protocol, there is always room for improvements. Hence the emergence of digital technology incorporated into traditional workflow.

The transition of traditional to full digital protocol is still on going and gradually developing. The aim is to try convert the physical data of the patient to digital data then can be used into treatment planning process and analyzation. To accommodate the transition of conversion, physical models are still used and taken with alginate or silicon, then plaster model are made. Afterwards, desktop scanners will scan the models for digitalization. There is also another option that a direct scanning will be performed on the impression instead pouring the plaster model. These two options have limitations that will alter the outcome of the digital data, for example, the material used for the cast model are specifically for scanning purposes, special coating will be sprayed on to the impression before the scanning. With all these factors affecting the trueness and precision of the information taken, led to the development of full digital workflow.

Digital workflow is not made specially for 3D printing applications; however, 3D printing requires a digital file format that all printers will need to execute the fabrication. Hence, from the digital workflow, the patient's information will be translated to digital data that can be used for creating standard tessellation language (STL) file, the file format that most printers require. The advantage of digital workflow is that the patient's data is collected digitally from the very first step with the help of 3D scanning imaging technology, there a lot new extra and intra oral scanners on the market accommodating different specialization of dentistry but all serving the same purpose of making a digital impression.(1,2,4,5)

The rapid development of 3D scanning imaging technology has led the 3D printing technology to advance and mature with more improved accuracy, new designed materials, and also higher efficiency. Also, 3D scanning imaging technique is changing how dentist work, further expanding the possibility different treatment approaches. The scanning imaging technology has provided options to allow dentist to work in a totally digital manner from the start to the end, or as a part that integrated to the traditional treatment workflow.

3D scanning technology can come in very handy in the day-to-day work routine for a treatment planning and an essential part for the 3D printing method, since a digital file will be required to print out the model and converting patient's oral condition into digital data will aid the process and enhance the printing outcome. There are varies types of 3 D scanner, but the main difference lies among the hard and soft tissue identification and accuracy, precision of the image that is generated.

After the scanning is completed, the data will then be processed by the computer aided design (CAD). The CAD system allows control of different parameters and also design and further modifications. After that, the STL file will be export to the printer. Depending on the brand and type of printer, final adjustments will be made before the fabrication such as size and colour. There are examples using additive process to create commercialized dental apparatus such as interim crowns, surgical guide, anatomical models and more. (6)

The application of 3D printing in dentistry are endless, involving in every single specialization with the cooperation of CAD and digital scanning. The physics of 3D printing allow numerous applications from pre-operation planning to actual dental treatment appliances and in this article, a further elaboration will be done to further discuss the technology of 3D printing in dentistry.

2. Objectives

Focus questions.

1.Discuss the 3D printing applications in different specialization of dentistry.

2.Discuss materials properties used for 3D printing applications in dentistry.

3. To explore the future of 3D printing applications in dentistry

3. Methodology

Information sources

Most research were done on electronic databases such as PubMed, Medline Complete, SpringerLink and Wiley Online library.

Search

The following keywords are used to help refine and focus on the topic regarding dentistry applications. The keywords used for the current article when using the electronic databases included the following:

- 3D printing in dentistry
- Stereolithography
- Digital light processing
- Photopolymer jetting
- Fused deposition modelling

Selection of articles

The criteria of selecting articles that has been limited to publications within the recent 20 years(2000-2021) , including scientific studies, case studies and literature reviews with relations of 3D printing in dental applications and also digital work flow.

Inclusion and Exclusion Criteria

The selection of the articles needed are followed by a list of inclusion criteria to refine the information obtained:

- Advantages of 3D Printing
- Digital workflow
- 3D printing in dentistry
- 3D printing applications
- 3D printing in prosthodontics
- 3D printing material in dentistry
- 3D printing material properties

Exclusion criteria:

- Articles without access to the title and abstract
- Lacking information regarding 3D printing
- 3D printing applications outside of dentistry
- Articles that are not English

4. Results

The results are obtained from the selected articles with certain criteria and keywords. 45 scientific articles were used in the current article with a combination of both in vitro and in vivo studies. Articles mentioning 3D printing applications in dentistry and the efficiency and benefits, and materials used for 3D printing in dentistry are included. The focus of the current article is to get a better understanding of how 3D printing is benefiting in different dental specializations, to explore how 3D printing technology can benefit the profession and improve the treatment quality. To follow up, comparisons are made to identify the advantages and disadvantages, allowing full comprehension of the development of 3D printing and finally to see how far the technology of digital printing can maximize the potential.

5. Discussion

5.1 Applications of 3D printing in dentistry

1. Medical modelling
2. Implant surgical guide
3. Treatment planning
4. Prosthodontics
5. Endodontics
6. Soft tissue regeneration

1. Medical modelling

Medical modelling was one of the earliest applications that adopted 3D printing technology, with such method, anatomical models can be recreated for better diagnosis and treatment planning. The model printing has led to further developments for further surgical and treatment planning for less invasive and better prognosis in dental treatments.

The medical modelling comes hand in hand with computer tomography (CT), the imaging technology not only allows a better prospective of the anatomical structure, but a creation of a digital data format for the design of the model that will be printed out. Cone beam computer tomography (CBCT) has become widely used in all fields of dentistry, from endodontics to oral maxillofacial surgery, the applications all serves one purpose, the creation of digital visualization, which provide the data needed for the 3D printing technology, and recreating patient's oral status and anatomical structure. This allows the fabrication of complex anatomical landmarks that are difficult to assess normally with traditional imaging system, also the printing technique allows magnifying structures in a larger scale, to provide a bigger prospective of certain structure or even teeth anatomy. (7)(8)(9)

Apart from treatment planning and diagnosis, 3D printing models can serve other purposes in fields of educational dentistry. The printing technique has shown an impact towards teaching and learning protocols to facilitate the learners to understand structures and designs of prosthodontic treatment preparations. The printing technique allowed first, a physical model that can be presented to students for better understanding with detailed anatomical landmarks, second, the possibility of mass production of one certain model to distribute out for group of learners, significantly reduce the time for manual fabrication time and cost of labor to prepare the models needed since the printing process can be done automated. And finally, to standardize the learning process for students, as each student will be learning from the exact same model, the level of training will then be standardized.(10)

More model examples were used in different training in dentistry. Traditionally, endodontic training was done with resin blocks or extracted human tooth, to simulate the working environment and practice the protocols of an endodontic treatment. The advantage of a resin blocks over a real extracted tooth is that learners can visually obturate the tooth with a better prospective of the anatomy of the canal, however, a clear resin block cannot mimic the real situation of an endodontic treatment since a real tooth is never visible. An extracted tooth can provide a simulation for a learner to experience a real-life scenario however, due to health and sanitary reasons, an extracted tooth might not be ideal, and not all extracted tooth comes with regular shape and sizes, hence, the training cannot be done in a standardized manner. With the help of 3D printing, tooth replicas can be made without any variance in canal anatomy and tooth structure. Designers can create the ideal training model with CAD and modify for different training purposes. And with this method, the material used for the model will be safe to use without any sanitary problems, furthermore, with the variation of printing technique, the model can be printed in different material and colour to mimic the real-life oral cavity, for example, tooth can be printed in clear transparent or natural shade of colour, anatomical landmarks can also be labelled with different colours. Most importantly, the designer will have the liberty to create multiple models to simulate difficult endodontic treatments, increasing the manual dexterity and familiarizing the protocol of the learning process. Models can be printed in mass numbers and even re used in situations, which will benefit for educational institutes.(11)

Additional applications for model printing are the fabrication of dental cast. Plaster cast has been utilized for a long period of time in dentistry and providing an exceptionally reliable option for replicating patients' oral cavity. As the potential of 3D printing significantly expanded and matured, dental cast can now be printed with different materials and techniques involving fused disposition modeling, digital light processing, and polymer jetting. Printing a cast comes with advantages such as dental cast can be more durable and long lasting and the freedom to choose the material that will be need for specific cases. However, certain aspects will be compromised in printing models, for example, material will have different physical properties, presenting different behaviors such as contractions or expansions, leading to inaccuracy of the cast and misjudgments in treatment planning. As all treatment in dentistry requires high precision, the results of 3D printing will be improved and adjusted.(12)(13)

Once a dental cast is obtained, the application for the model is endless, for example university adapting 3D printing as a method of training in the curriculum, allowing students to practice and train for different cases such as veneer preparation, dental bonding practice and interdisciplinary simulation model. The models are made with different density of materials to provide the sensation of different tooth structure and allowing students to learn about the anatomy of the treatment preparations. (14)

Further applications of the printing technique can be seen in the mockup approach, traditional dental protocols lacks the communications between the lab and patient, dentist rely heavily on mock ups made by the lab to demonstrate treatment outcomes and often the patient's requirements are not satisfied. To avoid multiple visit of the patient, digitalization can help bridge the communication of the labs and clinic. With virtual treatment planning, the patient can already have a provisional idea of the results, alongside with mockup approach, the predictability of the results can be enhanced. Traditional mockup approach is very technique sensitive, human errors can alter the results when digital workflow shows significant difference. To create the best results and accuracy, the errors must be eliminated during the workflow, milled mockup has then been introduced.(15) Clinical test has been done to compare the accuracy and results of both milled mockup and printed options, both options demonstrated slight dimensional changes when compare to the original model, but adaptation shown difference, poor fitting was observed in the milled mockups. Even with the milled mockups showing greater accuracy but the fitting might not be ideal, the clinical test that only had a small sample to compare both methods hence, more investigation will be put forward to discover the best option to achieve both fitting and accuracy. (16)

2. Implant surgical guide

The success of a well execute implant surgery relies on pretreatment planning and high precision to secure a good prognosis. A poor placement of an implant or discrepancy of location will trigger serious complications leading to the failure of the treatment and knowing that once the implant is embedded into the patient’s cavity, there are no room or possibility for adjustments unless the extraction of the whole implant body. Hence, the pretreatment planning must be accurate allowing precise implant allocation. With the advance technique of surgical guide, the placement protocol has been significantly changed, providing a guideline for the angulation, direction, and location of the implant body. Surgical guide can be done with different fabrication technology, 3D printing has been emerging as an available option while providing suitable characteristics to all dentist and surgeons to obtain a better control over the whole treatment process. Acrylic resin was one of the materials used for conventional surgical guide and has been performing with high standards of precision, however, the guide lacks important anatomical landmark information. To improve the conventional method, Computer tomography has been utilized to replicate the oral condition allowing detailed diagnosis and treatment planning and the digital data obtained can be used for the file format needed for the printing process.(17) Combining CT and CAD-CAM system, surgical guide can be done with milling process, there are evidence suggesting that 3D printing surgical guide has no clinical difference when compared to milled guides in terms of precision and trueness evaluations.(18) However, there are studies showing milled surgical guides can result in less deviation than 3D printed guides and even greater precision in the final position of implant placement.(19) However, the evidence did not affect the prognosis of the implant treatment. Hence, the deviation in using different fabrication methods is still to be studied. (18)

Different materials of the implant surgical guide have been compared as well, due to the physical properties of the guide, some materials show more flexion and some provides a rigid structure, taken into account of the physical properties, the accuracy of the guide can also be compromised. When comparing surgical guide made with thermoplastic and 3D printed materials, the statistics suggested no significant difference can be observed in terms of the angulation deviation. The measurement was done by calculating the head and apex of the implant body, to identify possible inclinations or misalignment. And furthermore, the 3D printed surgical guide shown promising results in terms of the location of the head and apex of the implant, further explaining the benefits of 3D printed technology when applied towards surgical guides.(20)

The printing design also plays a crucial part in model accuracy, most printing methods require supporting structure for the model that will be printed, hence the orientation of the model which will be printed can affect the accuracy of the outcome of the model. With studies showed that when the model was printed in a 0–45-degree angle on top of the supporting structure has significant difference in accuracy when compared to a 90-degree orientation, suggesting that the orientation of the design before printing needs to be considered before, to obtain the maximum precision. (21)

The protocol on fabricating a surgical guide involves in a lot of procedures, from the oral scanning imaging technique to the printing materials of the model can significantly alternate the precision result, including human errors, mechanical errors, scanning defects. The digitalization of 3D printing in surgical guide will continue aim to reduce the errors and increase the accuracy. (22)

3. <u>Treatment planning</u>

The digitalization of dentistry has increased the predictability of the treatment outcome with virtual planning and digital presentation, allowing patient to have a better understanding and meeting the expectations without repetitive visits, each design will be customized and tailored to each patient, also enhancing the communications between the technicians and dentist to work closely, and with alterations and corrections without wasting time and avoiding miscommunication. A model can be obtained from the digitalized visual design in the computer software, accuracy is the key factor since replicating the visual design into a physical model can involve complex procedures and conventional methods might included errors that can be avoided. With the printed 3D option, the accuracy can be ensured compared to traditional milling methods, without compromising significant accuracy and parameters.(23)

In a recent clinical case, the potential of 3D printing was demonstrated, the treatment plan for a patient that presents a full edentulous oral cavity was to perform an implant-prosthetic restoration with fixed prosthesis, Flapless implant placement was chosen in the case hence a lot of pretreatment planning was needed. The patient's oral cavity information was taken with Cone beam Computer tomography then transfer into a special treatment planning software to obtain a full virtual analysis followed by a digitalized planning of the implant surgery. After the planning of the implant placement in computer, the sites of the implant were decided and digitally subtracted creating a digital format of the mandible design with implant 'holes', afterwards a 3D master cast was printed out accompanied by a surgical guide for the implants. With the help of the 3D printing technology, the master model can accurately replicate the patient's oral anatomy, alongside with that, is dentists were able to predict and modify the implant surgery, creating a master cast with premade implants sites, that helped studying the oral relations and implant alignment on an articulator. After the models were made, dentists positioned the implants on the model with the prefabricated holes with the surgical guide, respecting the measurements of the implant's diameter and depth, creating a physical treatment outcome model with all the implants in place.

During the maxillary facebow transfer process, another 3D printed replica of the mandible was made to facilitate the transfer of the intraoral occlusal record to the 3D printed master model on the articulator.

The digitalization aided the surgical planning process of the flapless implant surgery, flapless implant surgical can often seem to be challenging since no visible bone anatomy will be observed before the implant placement and even with the surgical guide, the complications such as fenestrations or lesion in anatomical landmarks can happen. The computerized treatment plan alongside with the 3D model printed out provided a significant amount of information prior to the implant surgery, allowing the dentist to visualize the process and accurately plan the placement of the implant, minimizing the surgical risk and maximizing the prognosis of the treatment.

The role of the 3D printing technology in the clinical case mentioned above demonstrated two important advantages, the ability to visualize complex and hidden anatomical structures in physical 3-dimension manner and to create models that can facilitate and incorporate in the treatment. In combination with the digital oral imaging technique the data obtained allowed the creation of the STL file to print the model out, in addition to the digital design of the model to replicate the anatomical structure that clinician desire can be obtained in a physical form, further improves the results of the treatment. In the clinical case above, the substitution of traditional plaster cast to 3D printed models has been demonstrated. Traditional plaster cast has been in the market for decades with disadvantages such as technique sensitive and difficult to modify once the plaster is set. In the current example, with 3D printing technology, not only the accuracy will be increased, and the freedom of treatment design will also be enhanced. Master cast can be fabricated in multiple units at the same time, uniform productions of the master can be guaranteed, enhancing the efficiency of dental treatment. (24)

4. <u>3D printing as treatment option</u>

3D printing has shown a great potential in different specialization in dentistry, increasing the efficiency and prognosis of the treatment protocol, however, the applications mentioned previously are demonstrating how 3D printing can play a better auxiliary role in dentistry which leads to the question of can 3D printing applications be applied as a part of treatment option or even substituting conventional dental protocols.

The 3D printing technique shows the capability of replicating complex structure in each time accurately, with this advantage, dental treatment can be significantly revolutionized, the digitalization of dentistry will be connecting all the treatment steps together and facilitating each area of the protocol. From digital oral imaging to CAD and finally fabricating the model with 3D printing, all the steps are showing great potential of the replacement in traditional treatment options.

5. Prosthodontics

3D printing application has greatly benefited the treatments in prosthodontics, combining with CBCT technology, the digital advancement in dentistry provided the opportunity for 3D printing to widely applied and incorporated into prosthodontic appliances. Conventional prosthodontics treatment depends on highly skilled technician and well communication between lab and dentist, often result in unwanted errors or unsatisfied treatment outcome. With the 3D printed, these errors can be minimized and further improve treatment prognosis.

A good example of where 3D printing technology can come in place in prosthodontics is for the fabrication of dental prostheses. One of the most used application is for interim fix dental dentures, traditional interim prostheses are made with auto polymerizing acrylic resin, fabricated directly inside of the patient’s oral cavity, such methodology has been used for decades and still remains as the most used approach, however, there are drawbacks that made the traditional method less ideal for every situation, such as technique sensitive, labor intensive and also the discomfort sensation of the patient during the fabrication process in the oral cavity. The 3D printing technique provides an alternative option from the traditional method because of the drawbacks from traditional methods and with the digital oral imaging and CAD technology both assisting the rapid maturity of the printing of prosthetic devices. (25,26)

Applications for denture fabrication process might be limited to a several factors, (27)Firstly, dentures made with Milling methods have been showing promising results with accurate fit, the crucial key for the success of dental dentures is the retention between the denture and the oral mucosa, 3D printing dentures might be clinically acceptable, but more evidence is needed to provide clear indications. (28,29) Secondly, limitations from the mechanical properties of the material are another challenge for 3D printed models, dentures must have the characteristics to withhold stress from flexion and mastication during daily uses, materials used from 3D printing might cause deformation after repetitive stress and causing internal cracks leading to fracture of the denture. Conventional milled dentures are more resistant against stress and mastication force with greater flexural strength.(30,31) Lastly, the materials of choice for 3D printed models are prone to microbial colonization in contaminated oral cavity, studies have shown methods to battle against such matter by adding TiO_2 into the denture base to gain antibacterial ability, however, the addition of TiO_2 has been linked with weakening the denture and internal decomposition. (32,33) Hence, more studies and research are needed to discover the possibility of 3D printing applications in dentures.

Another prosthetic application of 3D printing will be interim crowns, serving as protection and maintaining the occlusal function and relationship.(34) Conventional methods heavily relies on the impression taken and also technique sensitive from the clinician, (35)defects from the process will also alter the strength of the structure, leading to possible fracture or damage. (36)With the help of digitalization and CAD/CAM methods, the shortcomings of conventional methods can be solved, clinicians now have different options to fabricate with CAD/CAM milling or printing. In dentistry, treatment goals are always to maximize patient's benefit, hence the crown must fulfill different criteria to rehabilitate the normal occlusal function. Marginal fitting is one of the most important criteria to determine the best option for fabricating the interim crown, but very dependent on the fabricating process, traditionally, direct method is predominantly utilized due to the rapid and straight forward process, however, the chemical and mechanical reaction of the polymerization might bring complications to the patient and causing discrepancies in the dimension of crown due to resin shrinkage. (37)The indirect method provides an alternative option without causing any potential risks and complications while working on a stone cast. With CAD/CAM milling technique and 3D printing introduced as indirect method into the fabrication of interim crowns, the comparison between the two methods have been made. Milling technique has been referred to as the subtractive method, while 3D printing method is the addictive method, due to the nature of subtractive method, the cutting bur diameter will limit the shape that is created on the material block which 3D printing provides the advantage of replicating the anatomy with highly level of accuracy while maintaining the structural integrity. Furthermore, economical cost of both methods is also crucial since milling method produced more un-used materials than 3D printing. (6)

Study has shown that 3D printing interim crowns with the technique of Polyjetting had promising results when compared to traditional direct and milling methods, especially in proximal marginal and internal region. 3D printing method demonstrated superior results to traditional direct method in terms of marginal fitting which can be understood due to the lack of resin shrinkage in 3D printing. When compared to milling, 3D printing technique proven that the fitting of the restoration especially in occlusal area has significantly lower discrepancy, which can be explained by the fabrication process of milling. Using the subtraction method, the material block is being deduced into the ideal design with cutting burs, since the bur size and range of motion may attribute towards the final dimension and accuracy, the result might deviate from a 3D printed model, modern day CAD system allows algorithmic correction during the design procedures, however, with such programmatic change, the trueness of the replication of the anatomy might be compromised. In contrast, 3D printing technique allows fabrication of layer by layer constructing the contour and dimension accurately. Even with different 3D printing techniques available on the market, the study has shown Polyjetting 3D printing provided concrete evidence for an improved fitting for interim crowns especially in focused regions and demonstrating that Polyjetting 3D printing could be compare with conventional milling technique, allowing clinicians to have an alternative approach during treatment planning. (6)

To add on, the internal fitting of the interim crown can also attribute towards the overall adaptation of the crown with study showing that 3D printing method had shown outstanding fit when compared to CAD/CAM milling methods. Milling technique shown difficulties reproducing sharp edge, protrude and undercut part when compared with 3D printing,(38) further proving that the potential of 3D printing is superior to conventional methods. (39)

Not only the 3D printer can contribute towards the discrepancies of the results, the method of converting patient's oral cavity to digital format can be significant. The digital model comparison can be generated by two different methods, first by conventional impression taking with polyvinylsiloxane elastomer then one method would be making a stone cast and combining intraoral optical scanning of the cast to generate the STL file, the alternative method was to utilize Cone Beam computer tomography to scan the conventional impression to obtain the data and converting to STL, followed by the exportation of the STL file to the printer. The measurements of the marginal and internal fitting were made to distinguish the accuracy of both data obtaining methods. CBCT might have shown less steps during the data acquisition due to the elimination of the process of fabricating the stone cast model, lowering the chances of human errors, and also demonstrating superior abilities in acquiring data in areas like undercuts and adjacent teeth. The results of the CBCT scanning method were acceptable with no significant difference in certain areas of the model. However, other areas shown discrepancies that might affect the adaptation which can be explained by the resolution of the CBCT and the conversion of data from CBCT to STL. Through the improvement and on-going development of higher resolution of CBCT and well-designed algorithm for the data conversion, CBCT could also be in consideration for digital acquisition of the oral cavity and part of the protocol for 3D printing process. (40)

Other specialization

6. Endodontics

The applications for 3D printing not only limit the use in certain areas of dentistry, for example endodontics has also benefitted by applying the technology to create endodontic access guides, to aid the burs to enter the canal with accuracy. Educational models can be made to simulate the canal anatomy and conditions to create clinical practices outside of live oral cavity to improve and practice. (11)

7. Oral Soft Tissue Regeneration

Biomaterial scaffolds are utilized in tissue engineering to provide initial structural support, allowing the cells to have a guide for adhesion and differentiation, continued by reconstructing the structure and anatomy of a missing tissue or facilitate the regeneration. With the power of creating complex structure, 3D printing can be used to produce various geometries and anatomy of scaffolds to perfectly adapt into oral cavity structure and replicate the tissue architecture to help generate the structural integrity that is required for different tissue regeneration treatments. (41)

5.2 Properties of materials used in 3D printing.

The 3D printing method differs from the traditional CAM method because the additive manufacturing or printing allows a selection of materials to be used at the same time during the fabrication thanks to the different types of printing method and printers. Printing models can consist of more than 1 material because of the printing technique, creating a combination of material which includes polymer with the bases of photoinitiated resin or thermoplastics and ceramics or even metal, used for dental applications.

Current 3D printing materials have shown strength in different properties such as stability and biocompatibility. Printed dental resins apparatus have shown promising results regarding the translucency, showing resistance towards different factors and colorants over time. However, the colour stability has shown changes over the course of observation period, showing colour variation possibility for dental apparatus. More investigations would be needed to consider more factors and properties, because the data collected from the current case were only done in 2 groups of thickness for the materials and often dental apparatus have multiple layers and thickness and also the dimension and design needed to be considered because light wavelength strikes and projects differently in different surfaces, specimen in current case only have an uniform shape which is different from normal dental apparatus.(42) Furthermore, patients' habit will be considered, frequency of intake of colorants such as cigarettes, wine and even food will alter the stability of colour in the material. Hence in treatment planning, patient's medical history and habits will be a factor for the application of 3D printing. More studies will be needed to prove the stability of 3D printing materials.(43)

Another consideration of the dental materials is the biocompatibility of the 3D printed materials, all applications from 3D printed must be safe for patient to place and inert into the oral cavity. Most used materials in dental printing process are approved with federal and departmental justifications. The clinical performance of most materials haven shown promising and predictable results, but considerations regarding the mechanical properties needs to be taken into consideration such as layers printed, material shrinkage and printing properties. (44) Furthermore, most materials used are photopolymer resins which have excellent properties proved by studies, the usage of resin has been widely applied in dentistry, and has been proven that was not toxic, while retaining promising mechanical properties. Consideration will be made since photopolymer resins are very sensitive to the photo curing time and the types of curing light. More investigation and development will be needed to demonstrate properties for dental applications. (45)

Limited studies were done to investigate the chemical and mechanical properties of the materials current used in different printers, and with the manufacturing company not publishing or releasing information regarding the composition, the difference between conventional and 3D printing material cannot be justified. Additionally, without the composition, limitations are set when identifying the complications, side effects and possible hazard indications towards human oral cavity. Regarding the mechanical properties, studies have shown that additive manufacturing materials show significantly lower flexural strength when compared to milled and conventional groups. And the printing orientation heavily influence the final outcome of the model. Hence, more research should be done to discover the suitable material for each treatment. (26)

5.3 Future of 3D printing in dentistry

The future of 3D printing is endless with the incorporation of digitalization in dentistry, with further development and research, new materials can be discovered, new designs of printers, new algorithm of digital data conversions, and even new printing techniques. The potential of 3D printing has not been fully discovered and understood; hence the applications are still limited towards a more auxiliary role however, with the promising evidence and data showing that 3D printing can fabricate similar quality of conventional dental treatment options, the applications can expand towards different specialities in dentistry, creating treatment and apparatus that are fully printed.

Printing materials can be further discovered and studied, the options that are on the market right now have room to improve but most of them are already safe to use and even showing long term sustainability. However, more structural rigidity and stability will be needed to provide alternative options for dental treatment.

Furthermore, cost of material and printer can be also improved, due to the new emergence of the 3D printing technique, the popularity for such equipment are still very conservative, hence, when clinicians wanting to apply and incorporate printing technology into treatment plans, economical consideration will be one of the disadvantages in contrast to traditional protocols.

Additionally, the level of knowledge to operate and master the system can be challenging, hence more education and promotion would be useful to help introduce the 3D printing technique into the general population of dentistry.

6. Conclusions

3D printing applications in dentistry are slowly emerging as one of the newest technologies that can bring dentistry a step ahead and closer to the future. With more studies and evidence showing that applications can be use in multiple specialization, the incorporation of printing can be seen as one of the major techniques in treatment protocol. The role of 3D printing is still conservative and auxiliary, the development for further involvement in dental treatment will rely on more advanced materials and printing methods that can demonstrate more characteristics that can compete with traditional methods and materials.

3D printing process has shown promising evidence in different fields of dentistry, for example, for treatment planning process and educational materials, using the advantage of replicating complex structure, 3D printing demonstrated the ability to create a visualization of anatomical structure and even designs of dental devices. Additionally, the possibility of unified mass productions to increase the efficiency and work rate. Furthermore, 3D printing provides accurate fabrication options for different dental apparatus, which can be compare with conventional methods, showing the emergence of the printing application can be incorporated into conventional workflow protocol. Although the applications are limited in some fabrications, for example, interim crowns and dentures, but with new discovery in materials and printer, possibility of creating prosthodontic definitive device will be made. And finally, 3D printing can provide an alternative option in terms of economical point of view because traditional techniques require more materials and steps to achieve what 3D printing can do. The integration of digital oral imaging, CAD and 3D printing, less time and steps are spent, allowing dentist to focus on the treatments and logistically, faster delivery and communications between labs and dentist to avoid mis communications and errors on lab work outcomes. With different printers and technique, the range of materials allows clinician to choose the approach needed for different treatments. The popular printing materials that are currently used already shown properties of stability, biocompatibility, and accuracy. However, when compared to traditional dental materials, more development and improvements should be made, to demonstrate additional mechanical and chemical properties.

The digitalization is playing a major role in the 3D printing development because the source of the file is always obtained from a digital file, the printing techniques have been established, the main direction of the research will be focusing on the materials and also protocols of printing to further improve the printing outcome. The future of 3D printing in dentistry will certainly have 3D printing as an option alongside with milling and even conventional fabrications. Following the success of CAD/CAM system and digital oral imaging technique, the benefit of 3D printing applications will be endless, alongside with more education and promotion, the acceptance of the technology will bring more options for clinician because the main goal of the clinician is always to maximize patient’s benefit.

7. Responsibility

Environmental

The applications for the 3D printing in dentistry can be beneficial for long term dental digitalization. The developments of new material and new printers will further provide more options for dental treatment, currently most printers use biocompatible and government approved materials to fabricate dental applications, which these materials have shown promising mechanical and chemical properties, one advantage that 3D printing has over conventional milling technique is that the material usage, additive printing method allows precise measurement of material usage and with that said, future development can focus on materials that are more ecofriendly and sustainable while maintaining the mechanical and physical properties.

Economic

The current cost of running a full digital system can be challenging for dental clinics that are interested to convert, with further developments made, the popularity of 3D printing technique will gradually increase and attracts more companies to compete and manufacture printers and materials that will allow more users to access, increasing the size of the market due to uprising demands. Currently, 3D printing is slowly emerging in parts of dental treatment and incorporating into conventional treatment protocols, in near future, the printing technology can be a major treatment option with accessible cost of usage.

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Annexes

3D printing in dentistry

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IN BRIEF

- Discusses the latest technologies in 3D imaging and printing that can be applied in dentistry.
- Suggests these technologies could be used in daily practice.

3D printing has been hailed as a disruptive technology which will change manufacturing. Used in aerospace, defence, art and design, 3D printing is becoming a subject of great interest in surgery. The technology has a particular resonance with dentistry, and with advances in 3D imaging and modelling technologies such as cone beam computed tomography and intraoral scanning, and with the relatively long history of the use of CAD CAM technologies in dentistry, it will become of increasing importance. Uses of 3D printing include the production of drill guides for dental implants, the production of physical models for prosthodontics, orthodontics and surgery, the manufacture of dental, craniomaxillofacial and orthopaedic implants, and the fabrication of copings and frameworks for implant and dental restorations. This paper reviews the types of 3D printing technologies available and their various applications in dentistry and in maxillofacial surgery.

INTRODUCTION

The term 3D printing is generally used to describe a manufacturing approach that builds objects one layer at a time, adding multiple layers to form an object. This process is more correctly described as additive manufacturing, and is also referred to as rapid prototyping.[1,2]

3D printing technologies are not all new; many modalities in use today were first developed and used in the late 1980s and 1990s[3] the author first treated a patient with the help of 3D printing in 1999 (Fig. 1).

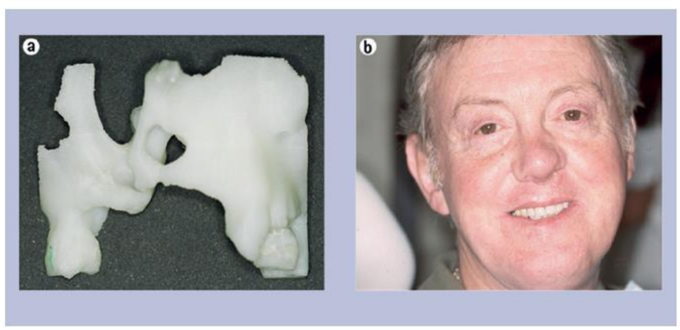

Fig. 1 The first patient treated by the author with the help of 3D printing in 1999. (a) Frontal view of the 3D printed medical model, printed with FDM technology, which shows the complex anatomy of the patient's cleft palate, before implant placement. (b) A recent image of the patient with implant supported bridgework in place

The term '3D printing', however, is relatively new, and has captured the public imagination. A great deal of hype surrounds the use of 3D printing which is hailed as a disruptive technology that will forever transform manufacturing. We have seen headlines in the international press describing the use of 3D printing to produce everything from fashion wear and architectural models to armaments (Fig. 2). However, the reality is different; 3D printed underwear would today be uncomfortable and 3D printed guns are dangerous – to the individual firing them. While we are very many

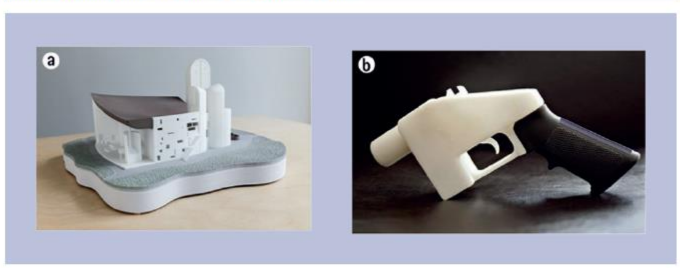

Fig. 2 (a) A 3D printed colour plaster architectural model of one of the most iconic examples of twentieth-century religious architecture designed by Le Corbusier. Model printed by digits2widgets.com. Photograph Chris Sullivan. (b) 3D printed gun. Production file controversially disseminated on the internet by American Cody Wilson, produced by digits2widgets.com for London's Victoria and Albert Museum collection

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From 3D imaging to 3D printing in dentistry – a practical guide

Von der 3-D-Bildgebung zum 3-D-Druck in der Zahnheilkunde – ein praktischer Leitfaden

Zusammenfassung

Die 3-D-Bildgebung stellt einen wesentlichen Bestandteil der Diagnostik und Behandlungsplanung in der Zahnmedizin dar. Die Umwandlung dieser digitalen Bilder in ein reales Objekt, das haptisch erfassbar ist, kann den Behandlern neue Möglichkeiten hinsichtlich der Patientenkommunikation, des Kompetenztrainings und der Behandlungsplanung eröffnen. Ziel dieses Beitrags ist es daher, einen praktischen Leitfaden von der 3-D-Bildgebung zum 3-D-Druck unter Verwendung kostengünstiger Drucker und Open-Source-Software zur Verfügung zu stellen. Mit den Programmen „3D Slicer", „MeshMixer" und der druckereigenen Software geben wir eine Schritt-für-Schritt-Anleitung zum „Rapid Prototyping" mittels „Fused Deposition Modeling" oder Stereolithographie. Als praktisches Beispiel druckten wir den Schädel eines Patienten mit dem Sathre-Chotzen-Syndrom, bei dem eine bignathe Umstellungsosteotomie durchgeführt wurde. Diese Anleitung ermöglicht es dem technisch interessierten Kliniker, patientenspezifische 3-D-Modelle selbst herzustellen, mit ihrer Hilfe Osteosyntheseplatten präoperativ vorzubereiten und die Vorteile des 3-D-Drucks in der Arzt-Patienten-Kommunikation für sich zu nutzen.

Abstract

3D imaging in dentistry plays an essential part in diagnostics and treatment planning. To transform digital images into a real object that can be experienced haptically may provide new opportunities to practitioners regarding patient communication, skills training, and treatment planning. Therefore, the aim of this article is to provide a practical guide from 3D imaging to 3D printing using low-cost printers and open source software; the authors used 3D Slicer software and a Meshmixer printer, including the printer's own software. The article presents step-by-step instructions on how to perform rapid prototyping via fused deposition modeling (FDM) and stereolithography (SLA). As an example, we printed the skull of a patient with Saethre-Chotzen syndrome who was undergoing maxillofacial surgery. The protocol explained here should enable the technically interested clinician to produce patient-specific 3D models in-house, prefabricate osteosynthesis plates, and take advantage of the benefits of 3D printing for dentist–patient communication.

Keywords: *3D imaging, 3D printing, FDM printing, SLA printing, rapid prototyping, preoperative treatment planning*

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Early Research & Development

by Terry Wohlers

The first attempt to create solid objects using photopolymers using a laser took place in the late 1960s at Battelle Memorial Institute. The experiment involved intersecting two laser beams of differing wave length in the middle of a vat of resin, attempting to polymerize (solidify) the material at the point of intersection. The photopolymer resin used in the process was invented in the 1950s by DuPont.

In 1967, Wyn K. Swainson of Denmark applied for a patent titled Method of Producing a 3D Figure by Holography on a similar dual laser beam approach. Subsequently, Swainson launched Formigraphic Engine Co. (Bolinas, CA) in hopes to further develop and eventually commercialize his technology. Work, reportedly, was still underway in 1994, although it never led to a commercially available system.

In the early 1970s, Formigraphic Engine Co. used the dual laser approach in the first commercial laser prototyping project, a process it called photochemical machining. In 1974, Formigraphic demonstrated the generation of a 3D object using a rudimentary system. Later, Formigraphic became Omtec Replication, apparently at a time when an alliance was formed with Battelle (Columbus, OH). Dr. Robert Schwerzel, then with Battelle, led the development of similar techniques with the help of DARPA funding. Co-developer Dr. Vincent McGinniss was one of the team members employed by Battelle.

In the late 1970s, Dynell Electronics Corp. was assigned a series of patents on *solid photography*. The invention involved the cutting of cross sections by computer control, using either a milling machine or laser, and stacking them in register to form a 3D object. Dynell merged with United Technologies Corp. in late 1977. As a result, an independent company called Solid Photography was formed and an affiliated retail outlet named Sculpture by Solid Photography was opened. In mid-1981, Sculpture by Solid Photography changed its name to Robotic Vision. Solid Photography and another company, Solid Copier, operated as subsidiaries of Robotic Vision at least until mid-1989.

Development of stereolithography

Hideo Kodama of the Nagoya Municipal Industrial Research Institute (Nagoya, Japan) was among the first to invent the single-beam laser curing approach, according to several sources. In May 1980, he applied for a patent in Japan, which later expired without proceeding to the examination stage, a requirement of the Japanese patent application process. Kodama claimed to have difficulty in securing funds for additional research and development.

In October 1980, Kodama published a paper titled Three-Dimensional Data Display by Automatic Preparation of a Three-Dimensional Model that outlined his work in detail. His experiments consisted of projecting UV rays using a Toshiba mercury lamp and a photosensitive resin called Tevistar manufactured by Teijin. The method involved black and white film used to mask and control the region of exposure, corresponding to each cross section. The paper also discusses the use of an x-y plotter device and optical fiber to deliver a spot of UV light. CMET used a version of this technique in its SOUP 530, 600, and 850 machines.

Stanley et al. BMC Oral Health (2018) 18:134
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BMC Oral Health

CASE REPORT

Open Access

Fully digital workflow, integrating dental scan, smile design and CAD-CAM: case report

Miguel Stanley[1], Ana Gomes Paz[1,3*], Inês Miguel[1] and Christian Coachman[2]

Abstract

Background: This report is a presentation of a clinical case that follows a full digital workflow.

Case presentation: A 47-year old man presented with pain in the TMJ (temporomandibular joint) and whose aesthetic concern was having a chipped maxillary central incisor veneer. The concern was solved following a fully digital workflow: it was applied the digital smile design protocol, as well as CAD-CAM monolithic lithium disilicate ceramic veneers and crowns (following a minimal invasive preparation approach). The aim of this rehabilitation was to solve a loss of vertical dimension, subsequent aesthetics and temporomandibular joint disorders.

Conclusion: Thanks to the evolution of technology in dentistry, it is possible to do a full digital case and solve problems such as loss of vertical dimension successfully. Nevertheless, more clinical studies are needed to obtain consistent results about the digital work flow compared to the conventional technique in loss of vertical dimension cases.

Keywords: Digital workflow, Digital planning, Digital smile design, Intraoral scanner, 3D printer, CAD-CAM, Minimal preparation, Monolithic lithium disilicate ceramic

Background

Digital work flow in dentistry has increased in recent years due to the headway made in technologies such as intraoral scanners and software programs, which have contributed to improve communication between the clinician and the dental technician. The Digital Smile Design (DSD) is a digital tool which provides, from a facial perspective, rehabilitative aesthetic planning, better communication between specialists and an improvement in the expected outcome of the treatments [1]. A dynamic documentation of the smile is an important step in the 2D/3D digital smile design process that can be performed in a entire digital flow and will help in the rehabilitative procedures. The advantages of using video documentation are that it facilitates and simplifies the documentation process, improves smile design, facial analysis, treatment planning, team communication and patient education [2]. The DSD could be converted into a conventional or virtual diagnostic model to facilitate subsequent clinical treatments, i.e. CAD-CAM restorations [3–7]. The preparations for minimally invasive treatments have become easily achievable in restorative dentistry because of the combination of the adhesive technique with restorative materials featuring translucent properties. Materials like lithium disilicate ceramic [8–11] have properties like those existing in natural teeth so they have presented positive outcomes [12, 13].

Another important tool that integrates the digital workflow are the intraoral scanners. These are powerful devices that allow an immediate determination of the quality of the impression and have the capacity to easily send the models to the laboratory using e-mail, thus reducing expense and time [14]. Nevertheless, there is limited literature about intraoral scanner potential capturing high quality impressions [15–24].

Computer-aided design (CAD) software is an essential tool since it is responsible for guiding robotic devices which create objects and assemblies in a virtual environment [25].

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CLINICAL ARTICLE

WILEY

Maxillary full-arch reconstruction using a sequenced digital workflow

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Abstract

Objective: Multi-staged treatment of a terminal maxillary arch from tooth-supported provisional to implant-supported final reconstruction using a fully digital workflow is reported. Each stage of the phased esthetically-guided reconstruction treatment plan, provisional restorations, and final restoration were executed in a virtual 3D environment prior to clinical treatment, providing CAD/CAM manufactured precision provisionals and final restoration that preserved the natural gingival architecture, function, and esthetics demanded by the patient.
Demonstrate the efficacy of using a digital workflow to fully restore a terminal maxillary arch with a precision implant-supported final prosthetic by instituting a multi-phase treatment plan designed to preserve the patient's gingival architecture, facial esthetics, and natural function.

Clinical Considerations: Sophisticated digital tools and software allow the dental team to work in a virtual environment to envision and execute the outcome of each stage of treatment prior to the patient appointment and to deliver an esthetically-guided precision final prosthesis that replicates the form, function, and occlusion of existing natural teeth.

Conclusions: Digital technologies provide clinicians and dental ceramists with sophisticated tools and software that advance the precision and execution of each phase of maxillary arch reconstruction in fewer patient visits and elevate the patient experience and treatment outcome.

Clinical Significance: Sophisticated digital tools and software allow the dental team to work in a virtual environment to envision and execute the outcome of each stage of treatment prior to the patient appointment and to deliver an esthetically-guided precision final prosthesis that replicates the form, function, and occlusion of existing natural teeth.

KEYWORDS
CAD/CAM, digital esthetic dentistry, fixed prosthodontics interim restorations, high strength zirconia, implantology, intraoral scanner

1 | INTRODUCTION

Full-arch reconstruction for patients presenting with terminal dentition in the maxillary arch can be executed using a variety methodologies.[1] For patients desiring an implant-supported solution, the treatment protocol often presented is immediate extraction followed by the placement of the number of implants deemed necessary to support an immediate provisional bridge followed by

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RESEARCH AND EDUCATION

Fit of interim crowns fabricated using photopolymer-jetting 3D printing

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ABSTRACT

Statement of problem. The fit of interim crowns fabricated using 3-dimensional (3D) printing is unknown.

Purpose. The purpose of this in vitro study was to evaluate the fit of interim crowns fabricated using photopolymer-jetting 3D printing and to compare it with that of milling and compression molding methods.

Material and methods. Twelve study models were fabricated by making an impression of a metal master model of the mandibular first molar. On each study model, interim crowns (N=36) were fabricated using compression molding (molding group, n=12), milling (milling group, n=12), and 3D polymer-jetting methods. The crowns were prepared as follows: molding group, overimpression technique; milling group, a 5-axis dental milling machine; and polymer-jetting group using a 3D printer. The fit of interim crowns was evaluated in the proximal, marginal, internal axial, and internal occlusal regions by using the image-superimposition and silicone-replica techniques. The Mann-Whitney *U* test and Kruskal-Wallis tests were used to compare the results among groups (α=.05).

Results. Compared with the molding group, the milling and polymer-jetting groups showed more accurate results in the proximal and marginal regions (P<.001). In the axial regions, even though the mean discrepancy was smallest in the molding group, the data showed large deviations. In the occlusal region, the polymer-jetting group was the most accurate, and compared with the other groups, the milling group showed larger internal discrepancies (P<.001).

Conclusions. Polymer-jet 3D printing significantly enhanced the fit of interim crowns, particularly in the occlusal region. (J Prosthet Dent 2017;118:208-215)

Interim restorations are essential not only for the protection of pulpal and periodontal tissues but also for the maintenance of oral function and esthetics.[1] To meet these goals, special care should be taken to ensure the shape and fit of such restorations.[1,2] The fit of restorations depends largely on the fabrication methods.[1,3] The techniques used for fabricating interim crowns can be divided into direct and indirect methods according to the manufacturing process.[4,5] In the direct method, the interim crown is fabricated immediately on the prepared tooth, whereas in the indirect method, the interim crown is fabricated on a stone cast and then delivered to the oral cavity.[5] Although the direct method is fast and straightforward, it has disadvantages. The exothermic heat released during resin polymerization in the direct method may cause thermal trauma to the tooth pulp.[6] Moreover, the residual resin monomer could harm the oral mucosa, causing lichenoid reactions or allergic stomatitis.[7] Another disadvantage of the direct method is the resin shrinkage caused by the reduction of the atomic distance in the low-molecular-weight monomers used.[8] This shrinkage causes dimensional discrepancies in the marginal, interproximal, and occlusal regions.[9] With the indirect method, the thermal and chemical risks to the tooth and mucosa are eliminated and the adaptation of the crown to the tooth is improved because the polymerization process is performed on a stone cast.[5]

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Three-dimensional printing to facilitate anatomic study, device development, simulation, and planning in thoracic surgery

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ABSTRACT

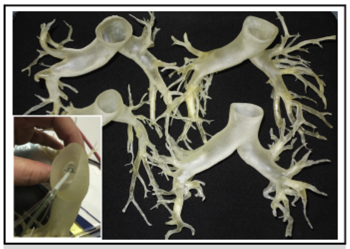
Background: The development and deployment of new technologies in additive 3-dimensional (3D) printing (ie, rapid prototyping and additive manufacturing) in conjunction with medical imaging techniques allow the creation of anatomic models based on patient data.

Objective: To explore this rapidly evolving technology for possible use in care and research for patients undergoing thoracic surgery.

Methods: Because of an active research project at our institution on regional lung chemotherapy, human pulmonary arteries (PAs) were chosen for this rapid prototyping project. Computed tomography (CT) and CT angiography in combination with segmentation techniques from 2 software packages were used for rapid generation and adjustment of the 3D polygon mesh and models reconstruction of the PAs. The reconstructed models were exported as stereolithographic data sets and further processed by trimming, smoothing, and wall extrusion.

Results: Flexible 3D printed replicas of 10 patient PAs were created successfully with no print failures; however, 1 initial test print with a 1 mm mural thickness was too fragile so the whole group was printed with a 1.5 mm wall. The design process took 8 hours for each model (CT image to stereolithographic) and printing required 97 hours in aggregate. Useful differences in anatomy were defined by this method, such as the expected greater number of proximal branches on the left versus right (2.5 ± 1.1 vs 1.0 ± 0.0; $P = .001$).

Conclusions: Reconstructed models of pulmonary arteries using 3D rapid prototyping allow replication of sophisticated anatomical structures that can be used to facilitate anatomic study, surgical planning, and device development. (J Thorac Cardiovasc Surg 2015;149:973-9)



Flexible 3D printed models with inset, showing their use testing a catheter prototype.

Central Message

Additive 3D printing (rapid prototyping) of specially processed medical images allows the creation of sophisticated pulmonary artery replicas that can be used to facilitate anatomic study, surgical planning, device development, and patient education.

Perspective

Three-dimensional printing is moving relatively quickly from the domain of manufacturing to medical disciplines and even into the homes of patients and doctors. This protean technology can interest all surgeons by improving their tools or replicating useful anatomic structures for planning operations. In this report, we detail using various software packages to convert CT images into pulmonary arteries to innovate catheter design. This article provides basic information on how to segment imaging data and also tabulates software and hardware resources for the reader. A downloadable STL file of our work is provided for the reader to view or print.

See Editorial Commentary page 980.

Supplemental material is available online.

Three-dimensional (3D) printing or additive manufacturing refers to any of the various processes for printing a 3D object.[1] Primarily additive processes are used, in which successive layers of material are laid down under computer control.[2,3] These objects can be of almost any shape or geometry, and are produced from a 3D model or other electronic data source. A 3D printer is a type of industrial robot.[1] Additive manufacturing technology requires digitized representation of geometrical data, which comes in stereolithographic (STL) or in additive manufacturing file formats.

This technology enables building accurate patient-specific 3D printed anatomic models that can be used for new surgical instrument development,[4] physical measurements, diagnosis, surgical planning, and presentation to patients.[5-8] Such

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Institutional funds were used for onsite printing of 1 prototype and for the procurement of software packages. Printing services for 9 of the described models were funded by an unrestricted grant from Incodema3D, which employs D.S.

S.K. conducted image translation and 3D process engineering yielding final STL files, image creation, and manuscript preparation. C.I. conducted prototype printing using a university printer and provided manuscript preparation. D.S. conducted oversight of industry prototype printing and made contributions to the manuscript limited to Table 2 and details of the industry manufacturing process. T.D. is the corresponding author, provided postprinting model analysis and data collection, study conceptualization and design, and manuscript preparation.

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REVIEW ARTICLE

Oral and Maxillofacial Radiology

Cone-beam computed tomography and the dentist

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Keywords
cone-beam computed tomography, dentistry, radiation dose, radiology.

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Abstract

Although cone-beam computed tomography (CBCT) is just 15 years old, it has revolutionized the practice of dentistry, so much so, there is hardly a dental specialty which has not been affected by this technology. Nevertheless, it presents the dentist with a number of important challenges. An initial steep learning curve must be addressed without unnecessary exposure to the patient. This is particularly important when the patient is a child.

Introduction

Although cone-beam computed tomography (CBCT) is just 15 years old, it has revolutionized the practice of dentistry, so much so, there is hardly a dental specialty which it has not yet affected.

What is cone-beam computed tomography?

Unlike multidetector computed tomography (MDCT; the now standard CT unit used in medicine), CBCT uses a cone beam instead of a fan beam (Figure 1).[1–3] This means that since the cone irradiates a larger volume in a single rotation (nowadays this rotation may be as little as 180°) the radiation dose imparted is much lower than that by a fan beam. Multiple rotations of the fan beam CT are needed to cover the same stretch of patient. MDCT can also achieve this by their multiple arrays of fan beams (X-ray head detector pairs; currently this is as many as 320 pairs) imparting a similar radiation dose, but in a fraction of the time.

CBCT's spatial resolution (image detail) is superior to that of MDCT, between twice and eight-times better. Furthermore, the spatial resolution of CBCT is just as good in all three planes (axial, coronal, and sagittal), whereas medical CT is only optimum in the axial plane. This is because CBCT produces isotropic cuberilles directly from the dataset without going through the voxel middleman (compare Figures 2 and 3). Although the best MDCTs can approach this by a different process the overall better spatial resolution of CBCT has so far not been remotely challenged.

When does cone-beam computed tomography properly complement the work of the dentist?

Osseointegrated implants were first developed by Brånemark and his team half a century ago,[4] since then it has completely transformed prosthodontics. In addition to excellent technical skills, careful assessment of the patient is necessary to ensure that the implant/s and subsequent restoration has the best chance of success. Although osseointegrated implants have achieved a considerable long-term success, as evidenced by a recent American Academy of Osseointegration systematic review,[5] the need for good pre-implant cross-sectional imaging has generally become to be viewed as essential for successful implants. When the bone height is inadequate for implants then grafts can be considered.[6] Table 1 shows that substantial literature on the value of CBCT to the implantologist is only recent:

Meglioli et al. 3D Printing in Medicine (2020) 6:30
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3D Printing in Medicine

REVIEW

Open Access

3D printed bone models in oral and cranio-maxillofacial surgery: a systematic review

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Abstract

Aim: This systematic review aimed to evaluate the use of three-dimensional (3D) printed bone models for training, simulating and/or planning interventions in oral and cranio-maxillofacial surgery.

Materials and methods: A systematic search was conducted using PubMed® and SCOPUS® databases, up to March 10, 2019, by following the Preferred Reporting Items for Systematic reviews and Meta-Analysis (PRISMA) protocol. Study selection, quality assessment (modified Critical Appraisal Skills Program tool) and data extraction were performed by two independent reviewers. All original full papers written in English/French/Italian and dealing with the fabrication of 3D printed models of head bone structures, designed from 3D radiological data were included. Multiple parameters and data were investigated, such as author's purpose, data acquisition systems, printing technologies and materials, accuracy, haptic feedback, variations in treatment time, differences in clinical outcomes, costs, production time and cost-effectiveness.

Results: Among the 1157 retrieved abstracts, only 69 met the inclusion criteria. 3D printed bone models were mainly used as training or simulation models for tumor removal, or bone reconstruction. Material jetting printers showed best performance but the highest cost. Stereolithographic, laser sintering and binder jetting printers allowed to create accurate models with adequate haptic feedback. The cheap fused deposition modeling printers exhibited satisfactory results for creating training models.

Conclusion: Patient-specific 3D printed models are known to be useful surgical and educational tools. Faced with the large diversity of software, printing technologies and materials, the clinical team should invest in a 3D printer specifically adapted to the final application.

Keywords: 3D printing, Additive manufacturing, Bone model, Surgical training, Preoperative planning, Simulation

Introduction

Technological development strongly drives the evolution of oral and cranio-maxillofacial surgery [1]. Among all the additive manufacturing (AM) processes, "three-dimensional printing" (3DP), often used synonymously with additive manufacturing, is playing an ever-growing role. This technology involves the fabrication of objects through the deposition of material using a print head, nozzle, or other printing technology [2]. It allows creating objects layer-by-layer through computer-aided design/computer-aided manufacturing (CAD/CAM). It was originally developed in the 1980s to accelerate the production of small and custom-designed objects, but it revolutionized the prototyping concepts and embraced many applications in manufacturing industries. Later on, AM's applications started to be integrated in several medical techniques and procedures, giving some important inputs to various domains, such as dentistry, maxillofacial surgery, orthopedics and neurosurgery. Frequent clinical applications of 3D printing in everyday practice include

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The Use of 3D Printed Tooth Preparation to Assist in Teaching and Learning in Preclinical Fixed Prosthodontics Courses

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Keywords
3D printer; dental education; tooth preparation.

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Abstract

Tooth preparation for fixed dental prostheses is not an easy procedure to understand spatially, especially for first-year dental students. This technical report describes an innovative technique for assisting learning in preclinical fixed prosthodontics courses. Ideal full-contour tooth preparations are digitally scanned and 3D printed to the exact specifications of the ideal preparation. Students and faculty use these printed tooth preparations as teaching and learning tools to facilitate in 3D visualization for fixed prosthodontics courses.

The term 3D printing is generally used to describe the manufacture of a physical object from a 3D digital model. The object is typically built one layer at a time, adding multiple layers to form the object. This process is more correctly described as additive manufacturing and is also referred to as rapid prototyping.[1] Since its development, 3D printing has been used in various fields such as architecture, mechanical engineering, and the food industry. One of the most important applications of 3D printing is in the medical industry. With 3D printing, surgeons can produce patient-specific 3D-printed models of patients' body parts or organs. They can use these models to plan and practice surgeries, potentially saving lives. Furthermore, rapid prototyping has been used in different fields of dentistry, including surgical planning, maxillofacial prosthesis fabrication, fixed and removable dental prosthesis fabrication, orthodontics, and implant dentistry.[2] The successful use of 3D printing has markedly advanced in the past few years with the commercial availability of 3D printing facilities and scanners and the construction of computer-aided design.[3] Desktop 3D printers usually use a liquid photopolymerizing resin composed of methacrylate acid esters, acrylic acid esters, and photo-initiators that harden upon exposure to ultraviolet light. This material provides objects that are accurate, lightweight, dense, and resistant to wear and damage.[2] However, the application of these technologies in dental education is in its infancy.

Using only conventional 2D images and illustrations tends to make visual recognition and skill acquisition in crown preparation difficult for dental students in simulation clinic exercises. These 2D images and illustrations do not provide students with a sense of depth, or view of the angles and walls of crown preparations.[4] Obtaining sufficient information about the size and the shape of an object is the key to being able to reproduce it successfully.[5] This new and innovative technique, the use of 3D printed tooth preparations, is used in preclinical teaching to help with visual recognition, and to motivate and facilitate dental student learning in preclinical simulation clinic exercises. The 3D-printed tooth preparations do not only assist in learning and teaching, but also reduce time for faculty course preparation, as they can be printed within hours and reduce costs compared to conventional stone study models that need to be impressed and poured. In addition, dental students can use them to compare their tooth preparations, as the 3D-printed tooth preparations exactly replicate dimensions of the ideal tooth preparations. The aim of this article is to introduce the use of 3D-printed tooth preparations in dental education to assist in teaching and learning of dental students in preclinical fixed prosthodontics courses.

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REVIEW

Endodontic applications of 3D printing

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Abstract

Anderson J, Wealleans J, Ray J. Endodontic applications of 3D printing. *International Endodontic Journal*, **51**, 1005–1018, 2018.

Computer-aided design (CAD) and computer-aided manufacturing (CAM) technologies can leverage cone beam computed tomography data for production of objects used in surgical and nonsurgical endodontics and in educational settings. The aim of this article was to review all current applications of 3D printing in endodontics and to speculate upon future directions for research and clinical use within the specialty. A literature search of PubMed, Ovid and Scopus was conducted using the following terms: stereolithography, 3D printing, computer aided rapid prototyping, surgical guide, guided endodontic surgery, guided endodontic access, additive manufacturing, rapid prototyping, autotransplantation rapid prototyping, CAD, CAM. Inclusion criteria were articles in the English language documenting endodontic applications of 3D printing. Fifty-one articles met inclusion criteria and were utilized. The endodontic literature on 3D printing is generally limited to case reports and pre-clinical studies. Documented solutions to endodontic challenges include: guided access with pulp canal obliteration, applications in autotransplantation, pre-surgical planning and educational modelling and accurate location of osteotomy perforation sites. Acquisition of technical expertise and equipment within endodontic practices present formidable obstacles to widespread deployment within the endodontic specialty. As knowledge advances, endodontic postgraduate programmes should consider implementing 3D printing into their curriculums. Future research directions should include clinical outcomes assessments of treatments employing 3D printed objects.

Keywords: 3D printing, autotransplantation, guided access, guided endodontic surgery, rapid prototyping, stereolithography.

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Introduction

Computer-aided design and manufacturing (CAD/CAM) applications emerged in the 1960s and 1970s, first employed by large aerospace and automotive companies (Cohn 2010). Cost-saving initiatives in the automotive industry increased growth and development of additive manufacturing (AM) using incremental deposition of material, which is an innovation over subtractive manufacturing (SM) where an object is cut from a block of material (van Noort 2012, Abduo *et al.* 2014). The term AM is used by the International Standards Organization and the American Society for Testing and Material (https://www.iso.org/obp/ui/#iso:std:iso-astm:52900:ed-1:v1:en). However, in medical and dental applications, the term 3D printing is commonly used. AM allows for greater intricacy, reduced waste and a wider selection of materials over SM (van Noort 2012, Abduo *et al.* 2014, Torabi *et al.* 2015, Kim *et al.* 2016).

Duret & Preston (1991) demonstrated the first dental application of CAD/CAM introducing a numerically controlled SM miller for the fabrication of fixed restorations (Duret & Preston 1991, Miyazaki *et al.* 2009). Although modernized SM is still the preferred method for fixed CAD/CAM restorations, limited material options and confining orientation requirements have precluded its use for other dental applications (van Noort 2012, Abduo *et al.* 2014, Torabi *et al.* 2015).

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THE JOURNAL OF PROSTHETIC DENTISTRY

RESEARCH AND EDUCATION

Dimensional accuracy and surface characteristics of 3D-printed dental casts

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ABSTRACT

Statement of problem. Although studies have reported the accuracy of 3D-printed dental casts, studies addressing cast distortion throughout the complete-arch range are lacking.

Purpose. The purpose of this in vitro study was to evaluate the dimensional accuracy of different areas in complete-arch casts made with various 3D printing methods.

Material and methods. A computer-aided design (CAD) reference cast was modified from a mandibular cast by adding 6 cylinders in the canine, second premolar, and second molar locations and 3 spheres to define a coordinate system. A total of 50 casts were printed with 5 group materials, which included fused deposition modeling (FDM), digital light processing (DLP1 and DLP2), photopolymer jetting (Polyjet), and stereolithography (SLA). After scanning the 3D printed casts, the overall consistency was examined by superimposing them on the CAD reference cast and measuring the deviations. For dimensional accuracy, cylinder top coordinates were extracted from each printed cast, and X-, Y-, and Z-deviations and the 3D deviation were calculated by subtracting the coordinates of the CAD reference cast from the cast values. Statistical analyses were conducted by the Kruskal-Wallis test and the Mann-Whitney post hoc test (α=.05). Surface characteristics were examined with photographs and scanning electron micrographs.

Results. FDM showed more systemic deviations than DLP, Polyjet, and SLA from superimposing analysis (P<.01). In the X-axis, FDM and DLP showed contraction, while Polyjet and SLA showed expansion (P<.01). In the Y-axis, FDM showed forward deviations on the right side and DLP showed contraction (P<.01). Three-dimensional deviation at each cylinder location was lowest in the left canine region, and deviations increased with distance from this site in all groups. The qualitative features of casts varied among 3D printers in terms of shape, surface smoothness, and edge sharpness.

Conclusions. FDM and DLP casts tended to contract, whereas casts in the Polyjet and SLA groups expanded buccolingually and anterioposteriorly. Vertically, deviations were smaller than those in the other directions. (J Prosthet Dent 2020;■:■-■)

With the development and increasing popularity of intraoral scanners, direct digital acquisition of the dental arch has become widely used.[1-7] The computer-aided manufacturing (CAM) process can be divided into 2 categories: subtractive manufacturing such as milling processes and additive manufacturing, also known as rapid prototyping or 3D printing.[8-13] Three-dimensional printing has undergone rapid evolution and application and in medicine accounts for up to 20% of overall CAM usage.[14-17]

When digital scans are obtained with an intraoral scanner, prostheses can be generated in the absence of physical casts.[18] Nevertheless, accurate replicas of the dental arch may be required to provide information about the intaglio and marginal fit, proximal contacts, and occlusion.[19] Physical casts are required when porcelain is applied manually and when information about the adjacent and occluding teeth is essential.[20] Casts can be generated from intraoral scanning data by milling or 3D printing.[21-26]

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Review

Accuracy of 3-Dimensionally Printed Full-Arch Dental Models: A Systematic Review

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Abstract: The use of additive manufacturing in dentistry has exponentially increased with dental model construction being the most common use of the technology. Henceforth, identifying the accuracy of additively manufactured dental models is critical. The objective of this study was to systematically review the literature and evaluate the accuracy of full-arch dental models manufactured using different 3D printing technologies. Seven databases were searched, and 2209 articles initially identified of which twenty-eight studies fulfilling the inclusion criteria were analysed. A meta-analysis was not possible due to unclear reporting and heterogeneity of studies. Stereolithography (SLA) was the most investigated technology, followed by digital light processing (DLP). Accuracy of 3D printed models varied widely between <100 to >500 µm with the majority of models deemed of clinically acceptable accuracy. The smallest (3.3 µm) and largest (579 µm) mean errors were produced by SLA printers. For DLP, majority of investigated printers (n = 6/8) produced models with <100 µm accuracy. Manufacturing parameters, including layer thickness, base design, postprocessing and storage, significantly influenced the model's accuracy. Majority of studies supported the use of 3D printed dental models. Nonetheless, models deemed clinically acceptable for orthodontic purposes may not necessarily be acceptable for the prosthodontic workflow or applications requiring high accuracy.

Keywords: 3-dimensional printing; additive manufacturing; dental models; accuracy; systematic review; full-arch

1. Introduction

Three-dimensional (3D) printing is an additive manufacturing (AM) process that allows conversion of digital models into physical ones through a layer-by-layer deposition printing process. 3D printing has been adopted in dentistry at an increasing rate and construction of dental models is one of the main applications of this promising technology in prosthodontics, orthodontics, implantology and oral and maxillofacial surgery, amongst others [1]. An essential prerequisite of dental models is creating an accurate replication of teeth and the surrounding tissues to serve their intended purposes as diagnostic and restorative aids for assessment, treatment planning and fabrication of various dental appliances and prostheses. Currently, gypsum casts poured from conventional impressions (e.g., alginates silicones, poly-sulphurs, ethers) are considered the gold standard for constructing dental models [2]. However, these cast models suffer a number of limitations, including a need for expedited processing of impressions, depending on the impression material; storage space for resultant casts; the cost of human and laboratory resources involved in fabrication; poor structural durability; and a propensity to dimensional changes over time [3]. In contrast, 3D printed models could offer a more

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3D printed simulation models based on real patient situations for hands-on practice

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keywords
3D printing; simulation model; 3D rapid prototyping; Prosthodontics; hands-on practice; preclinical education.

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Abstract

During the last few years, the curriculum of many dentistry schools in Germany has been reorganised. Two key aspects of the applied changes are the integration of up-to-date teaching methods and the promotion of interdisciplinarity. To support these efforts, an approach to fabricating individualised simulation models for hands-on courses employing 3D printing is presented. The models are based on real patients, thus providing students a more realistic preparation for real clinical situations. As a wide variety of dental procedures can be implemented, the simulation models can also contribute to a more interdisciplinary dental education. The data used for the construction of the models were acquired by 3D surface scanning. The data were further processed with 3D modelling software. Afterwards, the models were fabricated by 3D printing with the PolyJet technique. Three models serve as examples: a prosthodontic model for training veneer preparation, a conservative model for practicing dental bonding and an interdisciplinary model featuring carious teeth and an insufficient crown. The third model was evaluated in a hands-on course with 22 fourth-year dental students. The students answered a questionnaire and gave their personal opinion. Whilst the concept of the model received very positive feedback, some aspects of the implementation were criticised. We discuss these observations and suggest ways for further improvement.

Introduction

In the last few years, the dental curriculum of many dentistry schools in Germany has been reorganised (1). These changes aim to introduce interdisciplinary, up-to-date teaching methods into clinical and pre-clinical courses. We try to support this by implementing more realistic simulation models for hands-on practice to effectively prepare students for clinical practice.

In pre-clinical courses, dental students are used to practice with simulation models. Most of the simulation models during the pre-clinical courses at German dental schools are typodonts made by KaVo (Biberach, Germany) and Frasaco (Tettnang, Germany). Both companies offer simulation models with exchangeable plastic teeth in a perfectly shaped alveolar ridge. These models usually replicate healthy and straight teeth in a eugnathic bite situation. However, in reality, teeth are often tilted and rotated. This makes procedures that required consideration of the insertion direction, for example preparations for bridges, and veneer preparations more demanding. Furthermore, whilst Frasaco developed model teeth with caries, root canals and their fillings, in most cases, these products are not sufficient to imitate realistic patient situations that exhibit, for example wedge-shaped defects, defective fillings, chipping and abrasion. KaVo, on the other hand, introduced silicone moulds for the production of individual models. Although the models can be individualised with natural teeth and simulated teeth, the production is time-consuming and extracted human teeth are involved. An alternative to typodonts are virtual learning environments like the haptic dental trainer Simodont (Moog, Nieuw-Vennep, the Netherlands) (2). Whilst such systems might be useful to perform manual dexterity exercises (3), essential tasks such as impression taking or adhesive build-ups cannot be performed virtually.

A review of the literature shows that some authors have developed their own simulation models for particular dental procedures, before.

Wolgin et al. (4) developed and evaluated an endodontic simulation model for practicing the determination of the working length radiographically and endodontically. The model was created by embedding extracted human teeth in a self-cured resin matrix.

Güth et al. (5) developed an implant simulation model. The model was used in an implant dentistry education course which had been integrated in a pre-clinical course. This way, the students were able to train essential parts of implant surgery and

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RESEARCH ARTICLE

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Milled versus moulded mock-ups based on the superimposition of 3D meshes from digital oral impressions: a comparative in vitro study in the aesthetic area

Francesca Cattoni[1,2], Giulia Teté[2,3], Alessandro Mauro Calloni[1,2], Fabio Manazza[1,2], Giorgio Gastaldi[1,4] and Paolo Capparè[1,2*]

Abstract

Background: Aesthetic porcelain veneers proved to be a long-term reliable prosthetic solution, ensuring minimal invasiveness. The use of veneers requires an adhesive cementation technique, so maintaining as much enamel as possible is to ensure lasting success. A diagnostic mock-up is a key tool that allows a preview of the outcome of the aesthetic restoration: it is obtainable both in an analog and digital way. With the recent developments in impression technology and the ever so fast growing use of CAD-CAM technologies it is useful to understand the pros and cons of either one of these techniques (analog and digital) in order to identify the easier and more convenient workflow in aesthetic dentistry.

Methods: After taking pictures and impressions of the dental arcs of a patient in need of aesthetic rehabilitation, 52 resin models were produced and a digital drawing of the smile was outlined. Both an analog and a digital wax-up were obtained from two of the 52 models: the latter was obtained using digital impressions and a dedicated software. The analog wax-up was then used to produce 25 matrices that have later been used to mould 25 resin mock-ups using a traditional moulding protocol (Control Group - CG). The digital wax-up was used to mill 25 PMMA mock-ups. Each mock-up, both milled and moulded (total 50), was then laid on the other 50 resin models as a digital impression of it was taken. The STL. files of the milled mock-ups were compared with the 3D CAD wax-up made using a specific software. The STL. files of the analog printed mock-ups were compared with the traditional wax-up design. A statistical analysis was carried out to evaluate the difference between the groups.

Results: The statistical analysis showed a significant difference ($P > 0.01$) between the mean value of the distance between the points of the overlapping STL. meshes in GC (0.0468 mm) and in TG (Test Group - TG) (0,0109 mm).

Conclusions: The study showed a difference in accuracy between traditional moulded and milled mock-ups compared to their original wax-up. The data analysis reports that the digital method allows for greater accuracy. Within the limitations of this study, a fully digital workflow is to considered more reliable when it come to creating an esthetic mockup: the digital procedure has been shown to be more accurate than the one made manually which is much more operator dependent and it brings an increase to the chance of error, and that could ultimately affect the final result.

Keywords: Digital planning, Digital smile design, Mock up, Milling mock up, Digital workflow

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BMC Oral Health

RESEARCH ARTICLE

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The step further smile virtual planning: milled versus prototyped mock-ups for the evaluation of the designed smile characteristics

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Abstract

Background: Mock-up based approach allows the preview of the aesthetic rehabilitation, however, it is crucial that the mock-up does not differ from the expected aesthetic outcomes. With CAD-CAM technologies, it is possible to directly create mock-ups from virtual planned smile project, with greater accuracy and efficiency compared to the conventional moulded mock-ups. In this study, we investigated the trueness of mock-ups obtained with milling and 3D printing technology and a full digital work-flow system.

Methods: Ten adults subjects were included and digital smile design/digital wax-up were performed to enhance the aesthetic of maxillary anterior region. Ten milled mock-ups and 10 prototyped mock-ups were obtained from the original .stl file and a digital analysis of trueness was carried out by superimposing the scanned-milled mock-ups and the scanned-prototyped mock-ups to the digital wax-up, according to the surface-to-surface matching technique. Specific linear measurements were performed to investigate and compare the dimensional characteristics of the physical manufactures, the 3D project and the scanned mock-ups. All data were statistically analyzed. A clinical test was also performed to assess the fitting of the final manufacture.

Results: The prototyped mock-ups showed a significant increment of the transversal measurements ($p < 0.001$) while the milled mock-ups showed a significant increment of all vertical and transversal measurements ($p < 0.001$). The prototyped mock-ups showed good fitting after clinical tests while none of the milled mock-ups showed good adaptation (no fitting or significant clinical compensation required). Deviation analysis from the original 3D project reported a greater matching percentage for the scanned-milled mock-ups (80,31% ± 2.50) compared to the scanned-prototyped mock-ups (69,17% ± 2.64) ($p < 0.001$). This was in contrast with the findings from linear measurements as well as from the clinical test and may have been affected by a reductive algorithmic computation after digitization of physical mock-ups.

(Continued on next page)

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An assessment of template-guided implant surgery in terms of accuracy and related factors

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PURPOSE. Template-guided implant therapy has developed hand-in-hand with computed tomography (CT) to improve the accuracy of implant surgery and future prosthodontic treatment. In our present study, the accuracy and causative factors for computer-assisted implant surgery were assessed to further validate the stable clinical application of this technique. **MATERIALS AND METHODS.** A total of 102 implants in 48 patients were included in this study. Implant surgery was performed with a stereolithographic template. Pre- and post-operative CTs were used to compare the planned and placed implants. Accuracy and related factors were statistically analyzed with the Spearman correlation method and the linear mixed model. Differences were considered to be statistically significant at $P \leq .05$. **RESULTS.** The mean errors of computer-assisted implant surgery were 1.09 mm at the coronal center, 1.56 mm at the apical center, and the axis deviation was 3.80°. The coronal and apical errors of the implants were found to be strongly correlated. The errors developed at the coronal center were magnified at the apical center by the fixture length. The case of anterior edentulous area and longer fixtures affected the accuracy of the implant template. **CONCLUSION.** The control of errors at the coronal center and stabilization of the anterior part of the template are needed for safe implant surgery and future prosthodontic treatment. ***[J Adv Prosthodont 2013;5:440-7]***

KEY WORDS: Computer-assisted surgery; Dental implant; Accuracy

INTRODUCTION

Dental implant therapy has improved for the biomechanical restoration of function and the esthetic appearance of edentulous patients.[1,2] For successful implant therapy, prosthodontic and anatomical considerations should be included at the time of treatment planning. Panorama images have been widely used for many years to aid treatment planning. However, some limitations of panorama images are evident when assessing anatomical images, such as those of the inferior alveolar nerve and maxillary sinus floor, as well as when determining the path of implant fixtures for subsequent prosthodontic treatment. Computed tomography (CT) can overcome these faults and enables a stereoscopic approach to prosthodontic treatment.[3] Three-dimensional (3D) reformatted CT images have the potential to aid the spatial analysis of anatomical objects. For implant dentistry, CT imaging began to be actively applied in the 2000s through the use of 3D image-based guidance systems. Fortin *et al.*[4] suggested the following classification of computer-guided surgery: passive systems by the navigation tracker; semi-active systems, whose control depends on the

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RESEARCH ARTICLE

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Assessment of the reproducibility and precision of milling and 3D printing surgical guides

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Abstract

Background: Technology advancement has rising in the past decade and brought several innovations and improvements. In dentistry, this advances provided more comfortable and quick procedures to both the patient and the dental surgeon, generating less predictability in the final result. Several techniques has been developed for the preparation of surgical guides aiming at the optimization of surgical procedures. The present study aimed to evaluate the reproducibility and precision of two types of surgical guides obtained using 3D printing and milling methods.

Methods: A virtual model was developed that allowed the virtual design of milled ($n=10$) or 3D printed ($n=10$) surgical guides. The surgical guides were digitally oriented and overlapped on the virtual model. For the milling guides, the Sirona Dentsply system was used, while the 3D printing guides were produced using EnvisionTEC's Perfactory P4K Life Series 3D printer and E-Guide Tint, a biocompatible Class I certified material. The precision and trueness of each group during overlap were assessed. The data were analyzed with GraphPad software using the Kolmogorov–Smirnov test for normality and Student's *t* test for the variables.

Results: The Kolmogorov–Smirnov test showed a normal distribution of the data. Comparisons between groups showed no statistically significant differences for trueness ($p=0.529$) or precision ($p=0.3021$). However, a significant difference was observed in the standard deviation of mismatches regarding accuracy from the master model ($p<0.0001$).

Conclusions: Within the limits of this study, surgical guides fabricated by milling or prototyped processes achieved similar results.

Keywords: Surgical guide, Milling surgical guide, 3D printing surgical guide, Virtual guided surgery, CAD/CAM

Background

Rehabilitating a patient with an implant requires precise planning and special care during surgery. Placing a poorly planned implant can cause real problems, such as the perforation of critical anatomical structures, increased surgical duration, patient anxiety, pain, and stress. Therefore, presurgical planning using instruments such as tomography and surgical guides is essential [1–3].

The use of surgical guides in dentistry has provided patients and dental surgeons with greater flexibility, accuracy, and control of the procedure being executed [4, 5], resulting in a more comfortable postoperative experience for the patient and, by reverse planning, delivery of the immediate prosthesis or optimization of the final prosthetic result [6–8]. Different types of guides may be

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Split-Mouth Comparison of the Accuracy of Computer-Generated and Conventional Surgical Guides

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Edwin A. McGlumphy, DDS, MS[3]/Nancy L. Clelland, DMD, MS[3]

Purpose: *Recent clinical studies have shown that implant placement is highly predictable with computer-generated surgical guides; however, the reliability of these guides has not been compared to that of conventional guides clinically. This study aimed to compare the accuracy of reproducing planned implant positions with computer-generated and conventional surgical guides using a split-mouth design.* ***Materials and Methods:*** *Ten patients received two implants each in symmetric locations. All implants were planned virtually using a software program and information from cone beam computed tomographic scans taken with scan appliances in place. Patients were randomly selected for computer-aided design/computer-assisted manufacture (CAD/CAM)–guided implant placement on their right or left side. Conventional guides were used on the contralateral side. Patients underwent operative cone beam computed tomography postoperatively. Planned and actual implant positions were compared using three-dimensional analyses capable of measuring volume overlap as well as differences in angles and coronal and apical positions. Results were compared using a mixed-model repeated-measures analysis of variance and were further analyzed using a Bartlett test for unequal variance (α = .05).* ***Results:*** *Implants placed with CAD/CAM guides were closer to the planned positions in all eight categories examined. However, statistically significant differences were shown only for coronal horizontal distances. It was also shown that CAD/CAM guides had less variability than conventional guides, which was statistically significant for apical distance.* ***Conclusion:*** *Implants placed using CAD/CAM surgical guides provided greater accuracy in a lateral direction than conventional guides. In addition, CAD/CAM guides were more consistent in their deviation from the planned locations than conventional guides.* INT J ORAL MAXILLOFAC IMPLANTS 2013;28:563–572. doi: 10.11607/jomi.3025

Key words: *accuracy, computer-generated guides, conventional, implants*

Proper planning and placement are among the critical factors in implant dentistry.[1–3] Cone beam computed tomography (CBCT) and imaging software programs have been proven to facilitate accurate planning of implant lengths, diameters, and positions through three-dimensional (3D) visualization of anatomic limitations, available bone, and the desired restoration.[4] This virtual plan may be transferred to surgery using guides fabricated with computer-aided design/computer-assisted manufacture (CAD/CAM) methods. Current treatment planning for implant placement therefore involves the decision to use computer-generated guides or previous conventional techniques.[5–10] However, because CAD/CAM guides are considerably more expensive than conventional guides, an assessment of patient benefit, including predictability, may influence the choice of a CAD/CAM guide versus a conventionally fabricated guide.

Several recent clinical studies have compared actual implant placement to virtual plans to determine the predictability of CAD/CAM guides.[11,12] Ersoy et al[11] superimposed CBCT scans for 21 patients to compare planned implant positions with CBCT scans made after actual implant placement.[11] The differences between planned and actual implant positions were calculated.

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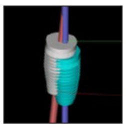
Accuracy of Implants Placed with Surgical Guides: Thermoplastic Versus 3D Printed



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This study was conducted to evaluate the accuracy of implants placed using two different guided implant surgery materials: thermoplastic versus three-dimensionally (3D) printed. A cone beam computed tomography (CBCT) scan previously obtained and selected for single-tooth implant replacement was converted into a Digital Imaging and Communications in Medicine (DICOM) file. All models were planned and exported for printing using BlueSkyBio Plan Software with the DICOM files. A total of 20 3D-printed mandibular quadrant jaws replicating the CBCT were printed by Right Choice Milling, as was the control model to accept the control implant. Previously, 10 thermoplastic and 10 3D-printed surgical guides had been made by the same lab technician at Right Choice Milling. One Nobel Biocare implant with a trilobe connection was placed per guide and replica jaw model pair. Implants were placed using the thermoplastic and 3D-printed surgical guides, representing the two test groups, following the Nobel Biocare guided surgical protocol. A total of 21 CBCT scans were then taken, one for the control implant and one for each test implant. The CBCT volume was converted to a DICOM file and transferred to Invivo5 software version 5.4 (Anatomage). The DICOM file of each test implant was superimposed over the DICOM file of the control. The deviation of the head of the implant, the deviation of the apex of the implant, and the angle of deviation were evaluated from measurements on the superimposition of the control and test implants. Mann-Whitney U test was used to test the null hypotheses at α = .05 and a confidence interval of 95%. Descriptive statistics were used for the average ± standard deviation. The implants placed with the thermoplastic surgical guides showed an average of 3.40 degrees of angular deviation compared to 2.36 degrees for implants placed with the 3D-printed surgical guides (P = .143). The implants placed with the thermoplastic surgical guides showed an average of 1.33 mm of deviation at the head of the implant compared to 0.51 mm for implants placed with the 3D-printed surgical guides (P < 0.001). The implants placed with the thermoplastic surgical guides showed an average of 1.6 mm of deviation at the apex of the implant compared to 0.76 mm for implants placed with the 3D-printed surgical guides (P < .001). There was no significant difference in the angular deviations of implants placed with thermoplastic surgical guides compared to those placed with the 3D-printed surgical guide. However, the locations of the implant head and implant apex were significantly more accurate for the implants placed with the 3D-printed surgical guides compared to those placed with the thermoplastic surgical guides. Int J Periodontics Restorative Dent 2018;38:113–119. doi: 10.11607/prd.3254

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With increasing patient esthetic concerns and the considerations required for implant location in relation to the bone and soft tissue, treatment planning for ideal implant placement is of the utmost importance. Therefore, many clinicians have shifted to the use of cone beam computed tomography (CBCT). CBCT eliminates some of the limitations associated with panoramic radiographs and is recommended as the best method for obtaining necessary information because of the ability to obtain cross-sectional imaging.[1]

Three-dimensional (3D) planning of the implant location allows for manipulation of individual implant positions with regard to depth, mesiodistal angulation and positioning, and labiolingual angulation and positioning.[2] It also encourages interdisciplinary communication between restorative dentists and surgeons, allowing for multiple variations of treatment plans to be evaluated and critiqued until the optimal treatment plan is attained and implemented for superior esthetic results.[3–5] The evolution of 3D implant planning has also had an effect on surgical placement. Surgical execution of the 3D plan is the most complicated step in the process of guided implant surgery.[6] The combination of 3D

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RESEARCH AND EDUCATION

Influences of build angle on the accuracy, printing time, and material consumption of additively manufactured surgical templates

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ABSTRACT

Statement of problem. Although desktop stereolithography (SLA) 3D printers and photopolymerizing resin have been used increasingly in dentistry to manufacture surgical templates, studies investigating their clinical application are lacking.

Purpose. The purpose of this in vitro study was to evaluate the effects of build angle on the accuracy, printing time, and material consumption of additively manufactured surgical templates made with a desktop SLA 3D printer and photopolymerizing resin material.

Material and methods. Fifty surgical templates were fabricated from 1 master digital design file using a desktop SLA 3D printer and photopolymerizing resin material at 5 different build angles (0, 30, 45, 60, and 90 degrees) (n=10). All surgical templates were digitized and superimposed with the master design file using best-fit alignment in the surface matching software program. Dimensional differences between the sample files and the original master design files were compared, and the mean deviations were measured in the root mean square (measured in mm, representing accuracy). The printing time and resin consumption for each specimen were recorded based on the information in the 3D printing preparation software program. ANOVA and the Fisher least significant difference (LSD) test were used to estimate the effects of build angles on the root mean square, printing time, and resin consumption (α=.05 for all tests).

Results. The groups 0 degree (0.048 ±0.007 mm) and 45 degrees (0.053 ±0.012 mm) had statistically significant lower root mean square values when compared with those of groups 30 degrees (0.067 ±0.009 mm), 60 degrees (0.079 ±0.016 mm), and 90 degrees (0.097 ±0.017 mm) (P<.001 for all comparisons, except P=.003 for groups 30 degrees versus 45 degrees). The group 90 degrees had statistically significant higher root mean square values than all other groups (P<.001 for all comparisons, except P=.010 when compared with the group 60 degrees). For the printing time, the group 0 degree required significantly less printing time than all other groups (hour:minute, 1:26 ±0:03, P<.001 for all comparisons). The group 90 degrees required significantly more printing time than all other groups (2:52 ±0:06, P<.001 for all comparisons). For resin consumption, the groups 0 degree (11.58 ±0.21 mL), 30 degrees (11.32 ±0.16 mL), and 45 degrees (11.23 ±0.16 mL) consumed similar amounts of resin. However, there was statistical significance between groups 0 degree and 45 degrees (P=.016). The group 90 degrees consumed the significantly least amount of resin (9.86 ±0.40 mL, P<.001 for all comparisons).

Conclusions. With a desktop SLA 3D printer, the 0-degree and 45-degree build angles produced the most accurate surgical template, and the 90-degree build angle produced the least accurate surgical template. The 0-degree build angle required the shortest printing time but consumed the most resin in the printing process. The 90-degree build angle required the longest printing time but consumed the least amount of resin in the printing process. (J Prosthet Dent 2020;■:■-■)

Surgical templates have been used to guide dental implant placement for accurate surgeries that would otherwise compromise anatomic landmarks, prosthetic restorability, and long-term stability.[1,2] Implant placement should be carefully planned and executed to place the implant in the ideal 3D position successfully.[3] The

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CLINICAL ORAL IMPLANTS RESEARCH

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Computer-supported implant planning and guided surgery: a narrative review

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Key words: accuracy, computer, guided surgery, implant, planning

Abstract

Aim: To give an overview of the workflow from examination to planning and execution, including possible errors and pitfalls, in order to justify the indications for guided surgery.

Material and methods: An electronic literature search of the PubMed database was performed with the intention of collecting relevant information on computer-supported implant planning and guided surgery.

Results: Currently, different computer-supported systems are available to optimize and facilitate implant surgery. The transfer of the implant planning (in a software program) to the operative field remains however the most difficult part. Guided implant surgery clearly reduces the inaccuracy, defined as the deviation between the planned and the final position of the implant in the mouth. It might be recommended for the following clinical indications: need for minimal invasive surgery, optimization of implant planning and positioning (i.e. aesthetic cases), and immediate restoration.

Conclusions: The digital technology rapidly evolves and new developments have resulted in further improvement of the accuracy. Future developments include the reduction of the number of steps needed from the preoperative examination of the patient to the actual execution of the guided surgery. The latter will become easier with the implementation of optical scans and 3D-printing.

The placement of endosseous implants has many pitfalls: movement of the patient while drilling, limited surgery time related to the use of local anesthesia, a restricted visualization of the operation field, mental transfer of two-dimensional radiographs into the three-dimensional surgical environment, esthetics, biomechanics, and functional constraints of the prosthetic treatment. Thus, during a limited time span and with a restricted view, the surgeon has to take numerous decisions while nurturing a conscious patient under aseptic conditions. Therefore, a thorough preoperative planning of the number of implants to be placed, their size, position, and inclination will free the surgeon's mind, allowing concentrating on the patient and the tissues handling.

As its development in the mid-nineties, guided implant surgery has quickly gained popularity (Verstreken et al. 1996, 1998; Jacobs et al. 1999). The introduction of the cone beam computed tomography (CBCT), enabling volumetric jaw bone imaging at reasonable costs and low radiation doses (Guerrero et al. 2006; Loubele et al. 2008), facilitated the collection of a large amount of information preoperatively (Jacobs & Quirynen 2014) including: an exact knowledge of the available bone volume and quality, the presence/location of anatomical structures and pathologies, and their relationship with the future restorative rehabilitation. As such the planning can be nearly completed preoperatively (Vercruyssen et al. 2008).

At this moment, different methods are available to transfer the "planned" information to the "clinical" situation. Jung et al. (2009) categorized these methods into "static" and "dynamic". Static systems apply surgical templates or implant guides, while dynamic systems transfer the selected implant position to the surgical area via visual imaging tools on a monitor. A dynamic system includes surgical navigation and computer-aided navigation technologies, and allows the surgeon to alter the implant position in real time.

The workflow of the static and dynamic guided surgery is summarized in Fig. 1. More

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BMC Oral Health

RESEARCH ARTICLE

Open Access

The step further smile virtual planning: milled versus prototyped mock-ups for the evaluation of the designed smile characteristics

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Abstract

Background: Mock-up based approach allows the preview of the aesthetic rehabilitation, however, it is crucial that the mock-up does not differ from the expected aesthetic outcomes. With CAD-CAM technologies, it is possible to directly create mock-ups from virtual planned smile project, with greater accuracy and efficiency compared to the conventional moulded mock-ups. In this study, we investigated the trueness of mock-ups obtained with milling and 3D printing technology and a full digital work-flow system.

Methods: Ten adults subjects were included and digital smile design/digital wax-up were performed to enhance the aesthetic of maxillary anterior region. Ten milled mock-ups and 10 prototyped mock-ups were obtained from the original .stl file and a digital analysis of trueness was carried out by superimposing the scanned-milled mock-ups and the scanned-prototyped mock-ups to the digital wax-up, according to the surface-to-surface matching technique. Specific linear measurements were performed to investigate and compare the dimensional characteristics of the physical manufactures, the 3D project and the scanned mock-ups. All data were statistically analyzed. A clinical test was also performed to assess the fitting of the final manufacture.

Results: The prototyped mock-ups showed a significant increment of the transversal measurements ($p < 0.001$) while the milled mock-ups showed a significant increment of all vertical and transversal measurements ($p < 0.001$). The prototyped mock-ups showed good fitting after clinical tests while none of the milled mock-ups showed good adaptation (no fitting or significant clinical compensation required). Deviation analysis from the original 3D project reported a greater matching percentage for the scanned-milled mock-ups (80,31% ± 2.50) compared to the scanned-prototyped mock-ups (69,17% ± 2.64) ($p < 0.001$). This was in contrast with the findings from linear measurements as well as from the clinical test and may have been affected by a reductive algorithmic computation after digitization of physical mock-ups.

(Continued on next page)

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WILEY

CLINICAL ARTICLE

Computer-guided implant surgery and full-arch immediate loading with prefabricated—metal framework—provisional prosthesis created from a 3D printed model

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Abstract

Objective: In this article, we describe the planning phase and clinical procedure where a CAD CAM 3D printed master model was utilized to create a prefabricated—titanium reinforced—fixed provisional prosthesis for a full-arch immediate loading after computer-guided implant placement.

Clinical Considerations: The clinical procedure should be performed based on digital planning through an advanced surgical planning software and following the guidelines of full-arch immediate loading protocol. The fact that the master model is fabricated under a computer-assisted design and computer-assisted manufacturing approach before implant placement makes the whole process considerably easier, faster, more precise and cheaper.

Conclusions: The use of a prefabricated—metal framework—provisional prosthesis for full-arch immediate loading created from a 3D printed master model seems to be a predictable treatment option when computer-guided implant surgery is performed.

Clinical Significance: The presented article described an interesting and innovative technique to optimize implant treatment based on digital technologies and 3D printing. The presented technique will help to diminish treatment costs and times especially for immediate loading procedures in fully edentulous patients because it allows to fabricate a prosthetic structure prior implant placement based on a 3D printing process.

KEYWORDS

3D printing, CADCAM, guided surgery, immediate loading, implants

1 | INTRODUCTION

The incorporation of virtual engineering into our profession and the digitalization of information are giving new perspectives and innovative alternatives for dental treatment modalities.[1] The use of computer implant planning software allows the combination of the radiographic, prosthetic, surgical, and laboratory fields under a common virtual scenario, permitting a complete virtual treatment planning.[2] A computer-assisted design and computer-assisted manufacturing (CADCAM) surgical guide provides a link between the virtual treatment plan and the actual surgery by transferring the simulated intervention accurately to the surgical site.[3] Nowadays 3D printers are one of the most utilized CAM process for surgical guides fabrication, bringing closer the concept of Digital Implantology to clinicians worldwide. Moreover, 3D printing has expanded the alternatives in oral reconstruction procedures, making the process of planning more precise, faster, cleaner, and cheaper.[4]

When indicated, the use of noninvasive surgical techniques such as flapless implant placement may offer several clinical advantages although maintaining similar survival rates to conventional implant placement procedures.[5–7] The avoidance of unnecessary flap release allows for the maintenance of the periosteal vascular bed, which helps ensure optimized blood supply. It is also well documented that patients treated with this approach may experience faster tissue healing and a better postsurgical course.[8,9] However, the use of a strict

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Research Article

Influence of the Postcuring Process on Dimensional Accuracy and Seating of 3D-Printed Polymeric Fixed Prostheses

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The postcuring process is essential for 3-dimensional (3D) printing of photopolymer-based dental prostheses. However, the deformation of prostheses resulting from the postcuring process has not been fully investigated. The purpose of this study was to evaluate the effects of different postcuring methods on the fit and dimensional accuracy of 3D-printed full-arch polymeric fixed prostheses. A study stone model with four prosthetic implant abutments was prepared. A full-arch fixed dental prosthesis was designed, and the design was transferred to dental computer-aided manufacturing (CAM) software in which supports were designed to the surface of the prosthesis design for 3D printing. Using a biocompatible photopolymer and a stereolithography apparatus 3D printer, polymeric prostheses were produced ($N = 21$). In postcuring, the printed prostheses were polymerized in three different ways: the prosthesis alone, the prosthesis with supports, or the prosthesis on a stone model. Geometric accuracy of 3D-printed prostheses, marginal gap, internal gap, and intermolar distance was evaluated using microscopy and digital techniques. Kruskal-Wallis and Mann-Whitney U tests with Bonferroni correction were used for the comparison of results among groups ($\alpha = 0.05$). In general, the mean marginal and internal gaps of cured prostheses were the smallest when the printed prostheses were cured with seating on the stone model ($P < 0.05$). With regard to the adaptation accuracy, the presence of supports during the postcuring process did not make a significant difference. Error in the intermolar distance was significantly smaller in the model seating condition than in the other conditions ($P < 0.001$). Seating 3D-printed prosthesis on the stone model reduces adverse deformation in the postcuring process, thereby enabling the fabrication of prostheses with favorable adaptation.

1. Introduction

Interim fixed dental prostheses are usually made in clinics with autopolymerizing acrylic resins [1, 2]. This conventional manual methodology is still the mainstream approach in fabricating fixed prosthodontics but is labor-intensive and uncomfortable for patients because the direct fabrication of prostheses is performed inside the patient's mouth, and heating occurs during polymerization. Because of these drawbacks, digital scanning and computer-aided design/computer-aided manufacturing (CAD/CAM) technologies are increasingly being used to fabricate interim polymeric prostheses [3, 4]. The oral anatomic shape is virtually registered using an optical scanner, and the scan data are imported into dedicated dental CAD software, in which the cementation space of the prosthetic crown is set and a final prosthesis is designed [5]. The design is then transferred to CAM software where the 3D image is divided into 2D cross-sectional images and processed to the polymeric prosthesis using additive manufacturing technologies [6]. The final fabrication process is the post-curing treatment of the printed prosthesis [6].

The 3D printing technologies have diversified treatment procedures and have become an alternative to manual and subtractive methods in medical and dental fields [7–10]. There are several different ways to print polymeric

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REVIEW ARTICLE

A review on chemical composition, mechanical properties, and manufacturing work flow of additively manufactured current polymers for interim dental restorations

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Abstract

Objectives: Additive manufacturing (AM) technologies can be used to fabricate 3D-printed interim dental restorations. The aim of this review is to report the manufacturing workflow, its chemical composition, and the mechanical properties that may support their clinical application.
Overview: These new 3D-printing provisional materials are typically composed of monomers based on acrylic esters or filled hybrid material. The most commonly used AM methods to manufacture dental provisional restorations are stereolithography (SLA) and material jetting (MJ) technologies. To the knowledge of the authors, there is no published article that analyzes the chemical composition of these new 3D-printing materials. Because of protocol disparities, technology selected, and parameters of the printers and material used, it is notably difficult to compare mechanical properties results obtained in different studies.
Conclusions: Although there is a growing demand for these high-tech restorations, additional information regarding the chemical composition and mechanical properties of these new provisional printed materials is required.
Clinical Significance: Additive manufacturing technologies are a current option to fabricate provisional dental restorations; however, there is very limited information regarding its chemical composition and mechanical properties that may support their clinical application.

KEYWORDS
3D printing, additive manufacturing technologies, interim restorations, material jetting, stereolithography

1 | OBJECTIVES

Additive manufacturing (AM) technologies can be used to fabricate 3D-printed interim dental restorations. The aim of this review is to report the manufacturing workflow, its chemical composition, and the mechanical properties that may support their clinical application.

2 | OVERVIEW

AM technologies refer to the fabrication of an object layer-by-layer.[1] Advancements in AM technologies have allowed for its integration into the digital workflow of prosthodontic applications. The American Section of the International Association for Testing Materials (ASTM) international standard organization establishes technical standards for a wide range of materials, products, systems, and services. The ASTM committee F42 on AM technologies determined 7 AM categories: stereolithography (SLA), material jetting (MJ), material extrusion or fused deposition modeling (FDM), binder jetting, powder bed fusion, sheet lamination, and direct energy deposition.[1–4] In dentistry, the most commonly used AM methods are SLA and MJ technologies.

For SLA manufacturing, a building platform is immersed in liquid resin which is then polymerized by an ultraviolet laser.[5–7] The laser traces a cross section of each layer. After the layer is polymerized, the

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BMC Oral Health

REVIEW

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3D printed complete removable dental prostheses: a narrative review

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Abstract

Background: The purpose of this paper is to review the available literature on three-dimensionally printed complete dentures in terms of novel biomaterials, fabrication techniques and workflow, clinical performance and patient satisfaction.

Methods: The methodology included applying a search strategy, defining inclusion and exclusion criteria, selecting studies and forming tables to summarize the results. Searches of PubMed, Scopus, and Embase databases were performed independently by two reviewers to gather literature published between 2010 and 2020.

Results: A total of 126 titles were obtained from the electronic database, and the application of exclusion criteria resulted in the identification of 21 articles pertaining to printed technology for complete dentures. Current innovations and developments in digital dentistry have successfully led to the fabrication of removable dental prostheses using CAD/CAM technologies. Milled dentures have been studied more than 3D printed ones in the currently available literature. The limited number of clinical studies, mainly case reports, suggest current indications of 3D printing in denture fabrication process to be custom tray, record bases, trial, interim or immediate dentures but not definitive prostheses fabrication. Limitations include poor esthetics and retention, inability to balance occlusion and low printer resolution.

Conclusions: Initial studies on digital dentures have shown promising short-term clinical performance, positive patient-related results and reasonable cost-effectiveness. 3D printing has potential to modernize and streamline the denture fabrication techniques, materials and workflows. However, more research is required on the existing and developing materials and printers to allow for advancement and increase its application in removable prosthodontics.

Keywords: Complete removable dentures, Digital dentures, CAD/CAM, 3D printed, Rapid prototyping, Additive manufacturing

Background

Despite the reduction in the incidence of edentulism in this generation cohort [1], the absolute number of edentulous patients is increasing due to the increase in life-expectancy [2–4]. Complete removable dental prostheses (CRDP) or complete dentures (CD) have been used to rehabilitate patients with complete edentulism for centuries [5]. Those prostheses meet the minimum social and physiological needs of the patients [6] and have not evolved significantly in recent years.

The most commonly used material for fabrication of conventional CRDP has been the polymer polymethyl methacrylate (PMMA) [7]. The material's relative ease of processing and repair, biocompatibility, and esthetic characteristics have led to increased acceptability by the patients [8]. Nevertheless, PMMA has numerous disadvantages including high polymerization shrinkage, susceptibility to microbial colonization from the oral

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RESEARCH AND EDUCATION

Comparison of denture base adaptation between CAD-CAM and conventional fabrication techniques

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ABSTRACT

Statement of problem. Currently no data comparing the denture base adaptation of CAD-CAM and conventional denture processing techniques have been reported.

Purpose. The purpose of this in vitro study was to compare the denture base adaptation of pack and press, pour, injection, and CAD-CAM techniques for fabricating dentures to determine which process produces the most accurate and reproducible adaptation.

Material and methods. A definitive cast was duplicated to create 40 gypsum casts that were laser scanned before any fabrication procedures were initiated. A master denture was made using the CAD-CAM process and was then used to create a putty mold for the fabrication of 30 standardized wax festooned dentures, 10 for each of the conventional processing techniques (pack and press, pour, injection). Scan files from 10 casts were sent to Global Dental Science, LLC for fabrication of the CAD-CAM test specimens. After specimens for each of the 4 techniques had been fabricated, they were hydrated for 24 hours and the intaglio surface laser scanned. The scan file of each denture was superimposed on the scan file of the corresponding preprocessing cast using surface matching software. Measurements were made at 60 locations, providing evaluation of fit discrepancies at the following areas: apex of the denture border, 6 mm from the denture border, crest of the ridge, palate, and posterior palatal seal. The use of median and interquartile range was used to assess accuracy and reproducibility. The Levine and Kruskal-Wallis analysis of variance was used to evaluate differences between processing techniques at the 5 specified locations (α=.05).

Results. The ranking of results based on median and interquartile range determined that the accuracy and reproducibility of the CAD-CAM technique was more consistently localized around zero at 3 of the 5 locations. Therefore, the CAD-CAM technique showed the best combination of accuracy and reproducibility among the tested fabrication techniques. The pack and press technique was more accurate at 2 of the 5 locations; however, its interquartile range (reproducibility) was the greatest of the 4 tested processing techniques. The pour technique was the most reproducible at 2 of the 5 locations; however, its accuracy was the lowest of the tested techniques.

Conclusions. The CAD-CAM fabrication process was the most accurate and reproducible denture fabrication technique when compared with pack and press, pour, and injection denture base processing techniques. (J Prosthet Dent 2016;116:249-256)

Complete dentures can be fabricated using several different processes. The goal of each technique is to produce a prosthesis that exhibits intricate mucosal adaptation resulting in good retention, stability, and support with minimal fabrication distortion.

Three popular denture processing techniques are compression molding, pouring a fluid resin, and injection molding. Compression molding in a conventional flask (pack and press) has been used for decades and is the most widely used technique. The fluid resin (pour) technique became popular because of decreased processing time. However, by increasing the speed of processing, undesirable features such as prosthetic denture teeth shift during processing, air entrapment, and poor bonding between denture base and teeth have been identified.[1,2] The injection molding technique was first described by Prior in 1942 and commercialized in 1970 by Ivoclar. It incorporates characteristics of both pack and press and pour processing, combining the benefits of heat processing with the decreased time of the pour

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Research Article

Quantitative Evaluation of Tissue Surface Adaption of CAD-Designed and 3D Printed Wax Pattern of Maxillary Complete Denture

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Objective. To quantitatively evaluate the tissue surface adaption of a maxillary complete denture wax pattern produced by CAD and 3DP. *Methods*. A standard edentulous maxilla plaster cast model was used, for which a wax pattern of complete denture was designed using CAD software developed in our previous study and printed using a 3D wax printer, while another wax pattern was manufactured by the traditional manual method. The cast model and the two wax patterns were scanned in the 3D scanner as "DataModel," "DataWaxRP," and "DataWaxManual." After setting each wax pattern on the plaster cast, the whole model was scanned for registration. After registration, the deviations of tissue surface between "DataModel" and "DataWaxRP" and between "DataModel" and "DataWaxManual" were measured. The data was analyzed by paired t-test. *Results*. For both wax patterns produced by the CAD&RP method and the manual method, scanning data of tissue surface and cast surface showed a good fit in the majority. No statistically significant ($P > 0.05$) difference was observed between the CAD&RP method and the manual method. *Conclusions*. Wax pattern of maxillary complete denture produced by the CAD&3DP method is comparable with traditional manual method in the adaption to the edentulous cast model.

1. Introduction

Before the complete dentures are finally produced and the problems become uncorrectable, a procedure of try-in refers to the wearing of a wax pattern, after the arrangement of artificial teeth, in the mouth of an edentulous patient to identify and fix any problems with denture design. Thus, complete denture try-in is a vital step in the design of complete dentures for restoring edentulous jaws.

Several key points should be confirmed during the try-in [1, 2], including good fit of the completed dentures on the edentulous alveolar ridge and no tilting, twisting, nor stretching of the denture base. Vertical distance, centric relation, occlusion, aesthetics, and phonetic function should also be checked. To best test these dynamic functions of complete denture requires that the dentures be of good retention and stability; that is, each denture must have a snug fit between the denture tissue surface and the edentulous alveolar ridge.

Computer-aided design (CAD) and computer-aided manufacturing (CAM) technology has been widely applied in multiple oral disciplines, especially in the field of fixed denture restoration [3–5]. However, the application of CAD/CAM in the design and development of complete dentures is still being explored. Kawahata et al. and Inokoshi et al. applied the RP technology in the coping of a complete denture [6, 7]. In their studies, a wax copy of old complete denture was produced and used to do try-ins to evaluate the aesthetics, comfort, and stability in patients. However, no studies have quantitatively evaluated the tissue surface adaption of 3D printed dentures in patients, and none have compared this method quantitatively against the traditional manual method. In the previous study we developed the first

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RESEARCH AND EDUCATION

Flexural strength of denture base acrylic resins processed by conventional and CAD-CAM methods

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ABSTRACT

Statement of problem. High flexural strength is one of the desirable properties for denture base resins, yet only few studies have evaluated the physical properties of newer denture bases such as computer-aided design and computer aided manufacturing (CAD-CAM) milled products.

Purpose. The purpose of this in vitro study was to compare the flexural strength of 3 different types of denture base resins: compression molded, injection molded, and CAD-CAM milled.

Material and methods. Three groups (n=10) of acrylic denture base resins were tested: injection molded, compression molded, and CAD-CAM milled resin. ISO-compliant, rectangular specimens were fabricated (64×10×3.3 mm) (n=30). Specimens were stored in water for 1 week, and flexural strength was measured by using a 3-point bend test until failure. The Student *t* test was used to evaluate differences in the flexural strength and modulus of elasticity among specimen groups. The Bonferroni formula was used to set significance at α=.017 to account for multiple comparisons among the 3 groups.

Results. The flexural strength of the CAD-CAM milled group was significantly higher than that of the other 2 groups (P<.001), while the strength of the compression molded group was significantly greater than that of the injection molded group (P<.001). The flexural modulus of the CAD-CAM group was significantly higher than that of the other 2 groups (P<.001).

Conclusions. CAD-CAM milled denture bases may be a useful alternative to conventionally processed denture bases in situations where increased resistance to flexural strength is needed. (J Prosthet Dent 2020;123:641-6)

Polymethyl methacrylate (PMMA) was introduced in 1936 and remains the denture base material of choice.[1,2] It is a colorless polymer of methyl methacrylate, and its high mechanical strength, modulus of elasticity, low water solubility, and dimensional stability make it a suitable denture base material.[1,2] Denture resins should be biocompatible, esthetic, cleansable, and easily repairable; adhere to denture teeth; and have adequate physical and mechanical properties.[1] These products should have adequate strength and toughness to endure forces generated during function while also being dimensionally stable under varying thermal conditions.[2] High flexural strength is essential because of the uneven force distribution the base will endure under load and as the alveolar ridge irregularly resorbs.[3] Hence, it should be able to resist plastic deformation and fatigue resistance under repeated loads.[4]

Different categories of denture PMMA are currently available. In heat-activated resins, used in compression or injection molded methods, thermal energy activates benzoyl peroxide, which initiates the polymerization process.[1,2] Alternatively, chemically activated or autopolymerized denture base resins do not require thermal energy but instead use tertiary amines to activate benzoyl peroxide.[1,2] Dentures made with autopolymerized resins have lower mechanical properties than those made with heat-activated resins because of excess residual monomer.[5] Although light-activated resin exhibits higher flexural strength than heat-activated PMMA, it also shows brittleness and greater variability because of the

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Comparison of Mechanical Properties of 3D-Printed, CAD/CAM, and Conventional Denture Base Materials

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Keywords
Acrylic resin; denture base; flexural strength; surface hardness.

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Abstract

Purpose: To evaluate and compare the mechanical properties (flexural strength and surface hardness) of different materials and technologies for denture base fabrication. The study emphasized the digital technologies of computer-aided design/computer-aided manufacturing (CAD/CAM) and three-dimensional (3D) printing.
Materials and Methods: A total of 160 rectangular specimens were fabricated from three conventional heat-polymerized (ProBase Hot, Paladon 65, and Interacryl Hot), three CAD/CAM produced (IvoBase CAD, Interdent CC disc PMMA, and Polident CAD/CAM disc), one 3D-printed (NextDent Base), and one polyamide material (Vertex ThermoSens) for denture base fabrication. The flexural strength test was the three-point flexure test, while hardness testing was conducted using the Brinell method. The data were analyzed using descriptive and analytical statistics ($\alpha = 0.05$).
Results: During flexural testing, the IvoBase CAD and Vertex ThermoSens specimens did not fracture during loading. The flexural strength values of the other groups ranged from 71.7 ± 7.4 MPa to 111.9 ± 4.3 MPa. The surface hardness values ranged from 67.13 ± 10.64 MPa to 145.66 ± 2.22 MPa. There were significant differences between the tested materials for both flexural strength and surface hardness. There were also differences between some materials with the same polymerization type. CAD/CAM and polyamide materials had the highest flexural strength values. Two groups of CAD/CAM materials had the highest surface hardness values, while a third, along with the polyamide material, had the lowest. The 3D-printed materials had the lowest flexural strength values.
Conclusions: Generally, CAD/CAM materials show better mechanical properties than heat-polymerized and 3D-printed acrylics do. Nevertheless, a material's polymerization type is no guarantee of its optimal mechanical properties.

Complete dentures have been used for many years, and they are the gold standard for treating edentulism.[1] Recent improvements in science and technology have provided digital methods for denture base production, including computer-aided design/computer-aided manufacturing (CAD/CAM) and three-dimensional (3D) printing.[2-5] Digital methods allow the production of a denture base in one block and provide the ability to attach prefabricated teeth with an appropriate adhesive. The advantages of digital methods are faster denture fabrication and fewer phases in the work process,[6] which can reduce the possibility of mistakes. With the further development of digital technology, there are now new 3D-printed materials from various dental manufacturers and more CAD/CAM materials for denture base fabrication. While the mechanical properties of conventionally polymerized denture base acrylics[7-11] and polyamide materials have been investigated and reported[12-16]—along with new data on mechanical properties of CAD/CAM dentures, even if scarce[17-19]—to our knowledge, no studies have been published on the mechanical properties of denture bases produced from 3D-printed materials.

Surface hardness testing and the three-point flexure test are regularly used for analyzing the mechanical properties of denture base materials.[2,9,15] The aim of this study was to employ such testing for examining the mechanical properties

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Original Research

Evaluation of Cleanability of a Titanium Dioxide (TiO_2)-coated Acrylic Resin Denture Base

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Clinical significance

It is difficult for denture wearers with physical disabilities to keep their removable dentures clean. In this study, we applied TiO_2 to an acrylic resin denture base surface to improve its ease of cleaning. It was demonstrated that the TiO_2 coating had a positive effect on the acrylic resin denture base by preventing the accumulation of plaque.

ABSTRACT

Purpose : The purpose of this study was to evaluate the cleanability of a titanium dioxide (TiO_2)-coated acrylic resin denture base.

Materials and Methods : Two groups of acrylic resin denture base plate specimens were prepared : 1) the TiO_2-coated group, and 2) the Polished group made using a conventional polishing method. The surface roughness and contact angle of plate specimens from both groups were measured. Each plate was immersed in an experimental bolus. Subsequently, the amount of experimental bolus residue left on the surfaces of the plates after ultrasonic cleaning was compared between groups. The groups were further divided into two groups with and without ultraviolet-A ray irradiation during cleaning.

Results : The surface roughness of the TiO_2-coated group was greater than that of the Polished group. Inversely, the contact angle of the TiO_2-coated group was smaller than that of the Polished group (one-tenth that of the Polished group). There was a significant reduction in the experimental bolus residue ratio on the surfaces of the TiO_2-coated plates. The use of ultraviolet-A ray irradiation was not significantly different. The decrease in the experimental bolus residue ratio of the TiO_2-coated group was believed to be due to the considerable improvement in the wettability of the plates.

Conclusion : The TiO_2 coating on an acrylic resin denture base had a positive effect on its ease of cleaning by preventing the accumulation of experimental bolus residue.

Key words

titanium dioxide, acrylic resin denture base, denture cleaning

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Original article

Biocompatibility of a titanium dioxide-coating method for denture base acrylic resin

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Biocompatibility of a titanium dioxide-coating method for denture base acrylic resin

Objectives: Ease of denture cleaning is of paramount importance in geriatric patients and those with limited dexterity. We have previously investigated methods of coating dentures with titanium dioxide (TiO_2) and reported the effects (self-cleaning and antibacterial) of such treatments in *in vitro* studies. This study was to verify the biocompatibility of a TiO_2-coated acrylic resin produced by the new coating method with spray-coating technique.

Methods: Specimens were prepared from denture base acrylic resin and polished up to grit #1000. The TiO_2-coating agent was sprayed onto the specimens using an airbrush gun. Specimens were then divided into 'polymethyl methacrylate (PMMA)', 'primer-coated PMMA' and 'TiO_2-coated PMMA' groups to be evaluated for biological safety using a hamster oral mucosa irritation test, a guinea pig skin sensitisation test and a rabbit intracutaneous test. The biological reaction was scored.

Results: Reaction scores were considerably <1.0, the acceptable limit set by the ISO, in all three tests. Indeed, in most samples, there was no deleterious effect at all.

Conclusion: These results tested on animals demonstrate that denture base resin coated with TiO_2 by this method does not cause irritation or sensitisation of the oral mucosa, skin or intracutaneous tissue and is therefore good biocompatibility for use in close proximity to oral mucosa and skin.

Keywords: dentures, titanium dioxide, coated materials, biocompatibility, geriatric dentistry.

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Introduction

Polymethyl methacrylate (PMMA) resin has long been used as a denture base material[1], because of its hardness and rigidity under masticatory pressure, ease of handling, good aesthetics and low price. However, despite its obvious suitability as a denture base material[2,3], PMMA is also susceptible to deterioration[4], surface roughness following fatigue, microbial adherence[5–7] and colonisation by bacteria due to water absorption[1].

Microbe adhesion to the denture surface befouls the oral cavity and can cause systemic infections (e.g. aspiration pneumonitis)[8,9]. Geriatric patients and those with limited dexterity (e.g. maniphalanx dysfunction or rheumatoid arthritis) find oral hygiene (OH) troublesome and require assistance from family or nursing staff[10]. However, although various mechanical, ultrasonic and chemical cleaning methods have been proven efficacious[11,12], these helpers often lack the OH knowledge to apply them. Hygienic denture materials would be invaluable in improving OH in denture wearers. We have previously reported on the coating method of titanium dioxide (TiO_2) application, which has photocatalytic effect (i.e. oxidation decomposition and super-hydrophilicity), and the viability of making dentures that can be cleaned simply by rinsing in water[13–15]. TiO_2 can be incorporated into the resin[11,16,17] to achieve the photocatalytic effect but requires approximately 5wt% TiO_2, which can weaken the material and cause internal decomposition through its photocatalytic effect. A preferable option is to use TiO_2-coating method, which does not alter the resin itself. Coating can be by brushing, dipping or spraying, which will influence the coating thickness and resilience to detachment[15,18]. We used a spray-coating technique using an airbrush gun, which produces a thin

Management of Provisional Restorations' Deficiencies: A Literature Review

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ABSTRACT

Provisional restorations are designed in order to protect oral structures and promote function and esthetics for a limited period of time, after which they are to be replaced by a definite prosthesis. They play a particular role in diagnostic procedures and continued evaluation of the treatment plan, as they should resemble the form and function of the definite rehabilitation that they precede. Therefore, interim treatment should satisfy the criteria of marginal adaptation, strength, and longevity. In complicated treatment plans that intend to last for extended periods of time, the function of provisional prostheses involves the possibility of relining, modification, or repair. These adjustments raise considerations regarding the strength of the resultant bond. Chemical composition of the base and repair material, surface characteristics of fracture parts, and time elapsed since the initial set of the rehabilitation should be considered in the decision of the appropriate repair material and technique. Proper pretreatment of the provisional components' surfaces is essential to ensure bonding as well.

The purpose of this article is to illustrate the management of provisional restorations' deficiencies. This article highlights possible failures of custom-fabricated provisional restorations, describes methods to prevent their occurrence, and discusses clinical techniques for their management. Finally, the proper combination of materials and surface preparation to achieve the optimum treatment outcomes are presented.

CLINICAL SIGNIFICANCE

Provisional restorations' failures and other deficiencies are encountered by clinicians on a daily basis. Adequate laboratory techniques and material combinations presented herein may contribute to their efficient and predictable modifications and repairs.

(J Esthet Restor Dent 24:26–39, 2012)

INTRODUCTION

According to the Glossary of Prosthodontic Terms,[1] "provisional or interim prosthesis or restoration is a fixed or removable dental or maxillofacial prosthesis designed to enhance esthetics, stabilization and/or function for a limited period of time, after which it is to be replaced by a definitive dental or maxillofacial prosthesis."

The interim treatment focuses on protecting pulpal and periodontal health, promoting guided tissue healing in order to achieve an acceptable emergence profile, evaluating hygiene procedures, preventing migration of the abutments, providing adequate occlusal scheme, and evaluating maxillomandibular relationships.[2–6] From the clinician's standpoint, provisional restorations play a key role in the diagnostic procedures and continued evaluation of the treatment plan, as they must resemble

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Review Article

Techniques of Fabrication of Provisional Restoration: An Overview

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A properly fabricated provisional restoration is important in achieving a successful indirect restoration. The importance of provisional restorations as an integral part of fixed prosthodontic treatment is evident from the abundance of the literature pertaining to their importance regarding margin fidelity, function, occlusion, and esthetics. There are a variety of techniques available to suit the individual needs of the clinician and of the clinical situation, from a single unit to a complete-arch provisional fixed prostheses.

1. Introduction

Fabrication of provisional restorations is an important procedure in fixed prosthodontics. Provisional restorations must satisfy the requirements of pulpal protection, positional stability, occlusal function, ability to be cleansed, margin accuracy, wear resistance, strength, and esthetics. They serve the critical function of providing a template for the final restorations once they have been evaluated intraorally [1].

Provisional restorations in fixed prosthodontic rehabilitation are important treatment procedures, particularly if the restorations are expected to function for extended periods of time or when additional therapy is required before completion of the rehabilitation [2].

Interim procedures also must be efficiently performed, because they are done while the patient is in the operatory and during the same appointment that the teeth are prepared. Costly chair side time must not be wasted, but the dentist must produce an acceptable restoration. Failure to do so results in the eventual loss of more time than was initially thought saved.

A well-made provisional fixed partial denture should provide a preview of the future prosthesis and enhance the health of the abutments and periodontium. The theories and techniques of fabrication for numerous types of provisional restorations abound in the dental literature [3].

Many procedures involving a wide variety of materials are available to make satisfactory interim restorations. As new materials are introduced, associated techniques are reported, and thus, there is even more variety. It is helpful principle that all the procedures have in common the formation of a mold cavity into which a plastic material is poured or packed.

Provisional restorations may be made directly on prepared teeth [4, 5] with the use of a matrix or indirectly by making an impression of the prepared teeth [6, 7]. A combination indirect-direct [8] technique is also possible which has evolved as a sequential application of these that involves fabrication of a preformed shell that is relined intraorally.

2. Search Strategy

A PubMed search of English literature was conducted up to January 2010 using the terms: provisional restorations, fixed partial denture, treatment restorations. Additionally, the bibliographies of 5 previous reviews as well as articles published in journal of prosthodontics, journal of prosthetic dentistry, general dentistry, and journal of american dental association were manually searched.

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In vitro study of fracture strength of provisional crown materials

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PURPOSE. The purpose of this report was to evaluate the effect of the fabrication method and material type on the fracture strength of provisional crowns. **MATERIALS AND METHODS.** A master model with one crown (maxillary left second premolar) was manufactured from Cr-Co alloy. The master model was scanned, and the data set was transferred to a CAD/CAM unit (Yenamak D50, Yenadent Ltd, Istanbul, Turkey) for the Cercon Base group. For the other groups, temporary crowns were produced by direct fabrication methods (Imident, Temdent, Structur Premium, Takilon, Systemp c&b II, and Acrytemp). The specimens were subjected to water storage at 37°C for 24 hours, and then they were thermocycled (TC, 5000×, 5-55°C) (n=10). The maximum force at fracture (Fmax) was measured in a universal test machine at 1 mm/min. Data was analyzed by non-parametric statistics (α=.05). **RESULTS.** Fmax values varied between 711.09-1392.1 N. In the PMMA groups, Takilon showed the lowest values (711.09 N), and Cercon Base showed the highest values (959.59 N). In the composite groups, Structur Premium showed the highest values (1392.1 N), and Acrytemp showed the lowest values (910.05 N). The composite groups showed significantly higher values than the PMMA groups (P=.01). **CONCLUSION.** Composite-based materials showed significantly higher fracture strengths than PMMA-based materials. The CAD-CAM technique offers more advantages than the direct technique. ***[J Adv Prosthodont 2015;7:27-31]***

KEY WORDS: Temporary crown; Provisional restoration; Composite; Methyl methacrylate; Fracture strength, CAD-CAM

INTRODUCTION

Provisional restorations are an important part of prosthetic therapy procedures with fixed prostheses (i.e., crowns and bridges).[1] Provisional restorations serve important roles during tooth preparation and until fitting, luting the final fixed restoration.[1-3] These include pulpal tissue protection against physical, chemical, and thermal injuries; maintenance of positional stability and occlusal function; and provision of the prepared teeth with strength, retention, and aesthetics, which are essential to clinical success. Polymethyl methacrylate (PMMA) resins and composite-based resins (CBR) are the most common materials used to fabricate provisional fixed dental prosthesis (FDP).[2,4,5] Their chemical natures differ; methacrylate resins use liquid/powder and are hand-mixed, and composite-based resins use paste/paste and are usually auto-mixed. The polymerization reaction of methacrylate resins initiates chemically (self-curing), while composite-based materials are available as both self-curing and dual-curing systems.

Fractures are a common cause of failure of provisional restorations. Although restorations should be designed to avoid failure, fractures can still occur. This may cause the patient discomfort and economic loss. Thus, the mechanical strength properties of provisional materials are important and should be considered to ensure the clinical success of provisional restorations.[6] Incorrect occlusion, bruxism, undercontoured pontics, and trauma are potential reasons

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Polymerization shrinkage-strain kinetics of temporary crown and bridge materials

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Affiliations
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Abstract

Objective: The purpose of this study was to measure the polymerization shrinkage kinetics of four commercially available polymer-based temporary crown and bridge materials, including the effect of ambient temperature.

Methods: Three dimethacrylate-based materials and one monomethacrylate-based material were investigated. The polymerization shrinkage-strains were measured by using the Bonded-disk method with initial specimen temperature at both 23 and 37 degrees C, with values particularly noted at 5, 10, and 120 min after mixing. Five recordings were taken for each material. The progress of the setting reaction and its temperature-dependence were evaluated by the kinetic curves, and net shrinkage and total shrinkage (inclusive of expansion magnitude) of each material were compared by independent sample t-test and one-way ANOVA.

Results: Most shrinkage occurred in the first 10 min after mixing although there was an early expansion especially with the monomethacylate in the first 5 min. At 120 min, the net shrinkage-strain at 23 and 37 degrees C of the materials used in this test ranged from 3.54 to 4.13%. The fastest setting dimethacrylate-based material and the monomethacrylate-based material showed higher shrinkage-strain than other materials. No significant differences of net shrinkage-strain were found between 23 and 37 degrees C, but higher shrinkage rates were measured at 37 degrees C than at 23 degrees C.

Significance: The Bonded-disk method is a suitable method for measuring temperature-dependence of shrinkage-strain of polymer-based temporary materials. The dimethacrylate-based materials are preferable to monomethacrylates for temporary restoration as judged by the magnitude of polymerization shrinkage-strain, the majority of which is apparent within 10 min from the start of mixing and may affect the clinical outcome.

Related information

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ORIGINAL ARTICLE

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Rapid prototyping in dentistry: technology and application

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Abstract Medical imaging has been used to provide information for diagnostic and therapeutic purposes. The use of physical models provides added values in these applications. Rapid prototyping (RP) techniques have long been employed to build complex 3D models in medicine. However, publications regarding the dental application of RP technologies are still rare. This paper reviews and discusses the basics and applications of RP techniques in dentistry: (1) construction of a computer aided design (CAD) model, including data acquisition, data processing, and the corresponding machines and CAD packages, (2) typical RP systems and how to choose them, and (3) current and potential use of RP techniques in dentistry. Practical application examples of RP techniques in dentistry are provided.

Keywords Computer aided design · Dentistry · Medical imaging · Rapid prototyping

1 Introduction

Medical imaging technologies involve from X-ray radiology to more advanced and refined medical imaging modalities such as computerized tomography (CT), magnetic resonance imaging (MRI), and laser digitizing [1–4]. These new technologies are able to provide detailed three-dimensional pictures of the anatomy of the area of interest and therefore valuable data for diagnostic and therapeutic usage [5,6]. Techniques have been developed, together with software and hardware, to represent the data in 3D on a 2D screen. Given the visualization provided by sophisticated software packages, the fabrication of physical models may seem superfluous. However, the display of a 3D volume on a 2D screen does not provide surgeons with a complete understanding of the patient's anatomy. Surgeons must learn to interpret the visual information in order to reconstruct mentally the 3D geometry. Recently, head-mounted displays, stereoscopic glasses, and holograms have been employed to complement the 2D screen to provide more realistic representations of 3D volume models. Unfortunately, there is still no physical feel of the area of interest, like the infection area or fracture size, until an operation is performed [7]. In short, there are several visualization issues that are being addressed but not yet resolved by virtual models. The construction of physical models is often necessary. Physical models are attractive to surgeons because they offer the opportunity to hold the model in hand and view in a natural fashion, thus providing surgeons a direct, intuitive understanding of complex anatomic details which otherwise cannot be obtained from imaging on screen. The use of physical models also creates improved prerequisites for planning and simulation of complex surgery. With a physical model at hand, a surgeon is able to exercise on the model with the usual surgical tools, enabling him/her to rehearse different surgical plans realistically. Based on this, surgery can be simulated in a way that is not possible even with the latest visualization technologies. Such an intensive planning of surgical procedures allows the selection of the best technical approach. Additionally, the communication between the surgeon and the patient before a complicated surgical procedure can be clearly improved by the use of physical models [8].

A physical model can be manufactured based on X-ray CT or MRI data. Several methods can be employed to fabricate a physical prototype. These methods can be divided into two categories: subtractive and additive. They all start with a 3D computer aided design (CAD) model of the anatomical area, which usually can be derived from X-ray CT or MRI data. The subtractive technique used is the conventional numerically controlled (NC) machining, generally milling [8]. In this case the shape of the model is milled from a block of polyurethane or other foam. The advantages include low material costs and the possibility that these models can be worked on with surgical

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Evaluation of internal fit of interim crown fabricated with CAD/CAM milling and 3D printing system

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PURPOSE. This study is to evaluate the internal fit of the crown manufactured by CAD/CAM milling method and 3D printing method. **MATERIALS AND METHODS.** The master model was fabricated with stainless steel by using CNC machine and the work model was created from the vinyl-polysiloxane impression. After scanning the working model, the design software is used to design the crown. The saved STL file is used on the CAD/CAM milling method and two types of 3D printing method to produce 10 interim crowns per group. Internal discrepancy measurement uses the silicon replica method and the measured data are analyzed with One-way ANOVA to verify the statistic significance. **RESULTS.** The discrepancy means (standard deviation) of the 3 groups are 171.6 (97.4) µm for the crown manufactured by the milling system and 149.1 (65.9) and 91.1 (36.4) µm, respectively, for the crowns manufactured with the two types of 3D printing system. There was a statistically significant difference and the 3D printing system group showed more outstanding value than the milling system group. **CONCLUSION.** The marginal and internal fit of the interim restoration has more outstanding 3D printing method than the CAD/CAM milling method. Therefore, the 3D printing method is considered as applicable for not only the interim restoration production, but also in the dental prosthesis production with a higher level of completion. ***[J Adv Prosthodont 2017;9:265-70]***

KEYWORDS: CAD/CAM milling system; 3D printing system; Interim crown; Fitness

INTRODUCTION

The interim restoration is an important part of the fixed prosthesis treatment, which is used from the time of tooth preparation to the time of final cementation.[1-4] In addition, it also has a role in protection of abutment teeth, dental pulp, and gingiva in case of unexpected situation such as delay in final prostheses fabrication and extension of the patient's visiting interval.[5-7]

The fixed interim prosthesis is manufactured in the dental lab or dental office in direct and indirect method.[8,9] It may be manufactured manually, but the manual work's dependence on the worker's skill and several processing steps may serve as a weakness. On the other hand, as CAD/CAM system is recently available for prosthesis production, the processing error may be reduced.[10] The CAD/CAM production results in consistently high quality prosthesis by using various materials, satisfying the demands of patients.[11] The prosthesis production method that uses the CAD/CAM system may be divided into the subtractive manufacturing and additive manufacturing. The CAD/CAM milling is the method to obtain the designed shape by grinding the materials of block or disc. This method may result in the waste of materials and strict maintenance, and has disadvan-

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Review

3D Printing Approach in Dentistry: The Future for Personalized Oral Soft Tissue Regeneration

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Abstract: Three-dimensional (3D) printing technology allows the production of an individualized 3D object based on a material of choice, a specific computer-aided design and precise manufacturing. Developments in digital technology, smart biomaterials and advanced cell culturing, combined with 3D printing, provide promising grounds for patient-tailored treatments. In dentistry, the "digital workflow" comprising intraoral scanning for data acquisition, object design and 3D printing, is already in use for manufacturing of surgical guides, dental models and reconstructions. 3D printing, however, remains un-investigated for oral mucosa/gingiva. This scoping literature review provides an overview of the 3D printing technology and its applications in regenerative medicine to then describe 3D printing in dentistry for the production of surgical guides, educational models and the biological reconstructions of periodontal tissues from laboratory to a clinical case. The biomaterials suitable for oral soft tissues printing are outlined. The current treatments and their limitations for oral soft tissue regeneration are presented, including "off the shelf" products and the blood concentrate (PRF). Finally, tissue engineered gingival equivalents are described as the basis for future 3D-printed oral soft tissue constructs. The existing knowledge exploring different approaches could be applied to produce patient-tailored 3D-printed oral soft tissue graft with an appropriate inner architecture and outer shape, leading to a functional as well as aesthetically satisfying outcome.

Keywords: 3D printing; oral soft tissues; gingiva; biomaterials; tissue engineering; PRF

1. Introduction

Recent years have seen an expansion of the field of three-dimensional (3D) printing, also referred to as additive manufacturing or solid freeform fabrication [1,2]. 3D printing technology allows the production of an individualized 3D object based on a material of choice and a specific computer-aided design. In the medical field, the possibility to include living cells in the procedure has lifted 3D printing to another level and opened a myriad of possibilities for the creation of different tissues. The new opportunities are now paving the way towards patient-tailored treatments. Several factors have contributed to the emerging applications of the 3D printing approaches. The development of a variety of printable biomaterials now offers more precise control of scaffold inner architecture and outer shape. The available analytical digital tools offer quick and precise acquisition and documentation of the patient-specific situation in 3D. An easy transfer of digital data allows the design of anatomically perfectly shaped structures that can be customized for each patient. The expiration of the key 3D printing patents has substantially decreased the cost of printers. The rapid developments of these

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Color and Translucency Stability of Three-Dimensional Printable Dental Materials for Crown and Bridge Restorations

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Abstract: The purpose of this study was to examine and compare color and translucency stability of three-dimensional (3D) printable dental materials for crown and bridge restorations. Five different materials were investigated, and twelve disc-shaped specimens of two different thicknesses (1 and 2 mm) were prepared using a digital light processing 3D printer. Color measurements were made according to the CIELAB color scale (L*, a*, and b*) using a spectrophotometer 1 h, 1 day, 1 week, one month, and six months after post-curing of the materials, and the translucency parameter (TP) was calculated. The L*, a*, b*, and TP values were compared among the different materials and storage periods using repeated measures analysis of variance. Color and translucency changes of the specimens after the different storage periods were compared with 1 h measurements to determine whether they exceeded clinically perceivable thresholds. The L*, a*, b*, and TP values showed significant differences according to the storage periods, as well as among the materials. Until one month, some materials demonstrated distinct color differences, while others showed small color differences below a clinically perceivable threshold. The translucency differences were not clinically perceivable for any specimen. After six months, all specimens demonstrated large color changes, whereas the changes in translucency were relatively small. In conclusion, the color of 3D printable dental materials changed with time, and the differences varied with the materials used. On the contrary, the changes in translucency were small. Overall, the materials became darker, more yellowish, and more opaque after six months of water storage.

Keywords: color stability; translucency; three-dimensional printing; dental material; crown and bridge

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1. Introduction

In recent years, three-dimensional (3D) printing technology has been rapidly developed and widely utilized in various areas. In particular, in the dental field, 3D printing has become popular as an additive manufacturing method for dental restorations or laboratory products [1,2]. Moreover, it can be used in synergy with other digital technologies, such as computer-aided design/computer-aided manufacturing (CAD/CAM) or cone-beam computed tomography (CBCT). Currently, 3D printing is widely deployed in various dental treatment procedures, such as prosthodontic rehabilitation, dental implants, mandibular reconstructions, surgical and nonsurgical endodontics, and orthodontics [3–6]. 3D printing has made dental treatment procedures more accurate, efficient, and predictable, and it is gradually replacing traditional methods.

Currently, 3D printed dental restorations are mainly used as provisional or interim restorations for fixed prostheses, for example, as temporary crowns and bridges, as well as removable prostheses such as temporary dentures [7]. In many clinical situations,

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Evaluation of the Color Stability of 3D-Printed Crown and Bridge Materials against Various Sources of Discoloration: An In Vitro Study

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Abstract: Recent advances in three-dimensional (3D) printing have introduced new materials that can be utilized for dental restorations. Nonetheless, there are limited studies on the color stability of restorations using 3D-printed crowns and bridge resins. Herein, the color stability of conventional computer-aided design/computer-aided manufacturing (CAD/CAM) blocks and 3D-printing resins was evaluated and assessed for their degrees of discoloration based on material type, colorant types (grape juice, coffee, curry, and distilled water (control group)), and storage duration (2, 7, and 30 days) in the colorants. Water sorption, solubility, and scanning electron microscope (SEM) analyses were conducted. A three-way ANOVA analysis showed that all three factors significantly affected the color change of the materials. Notably, the discoloration (ΔE_{00}) was significantly higher in all 3D printing resins (4.74–22.85 over the 30 days) than in CAD/CAM blocks (0.64–4.12 over the 30 days) following immersion in all colorants. 3D-printing resins showed color differences above the clinical limit (2.25) following storage for 7 days or longer in all experimental groups. Curry was the most prominent colorant, and discoloration increased in almost all groups as the storage duration increased. This study suggests that discoloration must be considered when using 3D printing resins for restorations.

Keywords: 3-D printing; CAD-CAM; dental prosthesis; staining

1. Introduction

Recently, manufacturing restorations using computer-aided design/computer-aided manufacturing (CAD/CAM) has become an important process in dentistry and has replaced traditional methods in many areas. The CAD/CAM system, comprising optical scanners, the CAD software, and the manufacturing equipment, is gradually being used in dental clinics due to its advancement in technology [1,2]. Compared to the conventional dental restoration manufacturing process, this new method has simpler and more accurate procedures and better processing precision [1,2]. In addition, dentists and dental technicians can observe and communicate the design of the prosthesis digitally, and the data of the design can be stored as a digital file [3–6].

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A Review on the Biocompatibility of PMMA-Based Dental Materials for Interim Prosthetic Restorations with a Glimpse into Their Modern Manufacturing Techniques

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Abstract: This paper's primary aim is to outline relevant aspects regarding the biocompatibility of PMMA (poly(methyl methacrylate))-based materials used for obtaining interim prosthetic restorations, such as the interaction with oral epithelial cells, fibroblasts or dental pulp cells, the salivary oxidative stress response, and monomer release. Additionally, the oral environment's biochemical response to modern interim dental materials containing PMMA (obtained via subtractive or additive methods) is highlighted in this review. The studies included in this paper confirmed that PMMA-based materials interact in a complex way with the oral environment, and therefore, different concerns about the possible adverse oral effects caused by these materials were analyzed. Adjacent to these aspects, the present work describes several advantages of PMMA-based dental materials. Moreover, the paper underlines that recent scientific studies ascertain that the modern techniques used for obtaining interim prosthetic materials, milled PMMA, and 3D (three-dimensional) printed resins, have distinctive advantages compared to the conventional ones. However, considering the limited number of studies focusing on the chemical composition and biocompatibility of these modern interim prosthetic materials, especially for the 3D printed ones, more aspects regarding their interaction with the oral environment need to be further investigated.

Keywords: biocompatible materials; poly(methyl methacrylate); interim dental prosthesis; three-dimensional printing *polymers*

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Article

Mechanical Properties and Biocompatibility of Urethane Acrylate-Based 3D-Printed Denture Base Resin

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Abstract: In this study, five urethane acrylates (UAs), namely aliphatic urethane hexa-acrylate (87A), aromatic urethane hexa-acrylate (88A), aliphatic UA (588), aliphatic urethane triacrylate diluted in 15% HDD (594), and high-functional aliphatic UA (5812), were selected to formulate five UA-based photopolymer resins for digital light processing (DLP)-based 3D printing. Each UA (40 wt%) was added and blended homogenously with ethoxylated pentaerythritol tetraacrylate (40 wt%), isobornyl acrylate (12 wt%), diphenyl (2,4,6-trimethylbenzoyl) phosphine oxide (3 wt%), and a pink acrylic (5 wt%). Each UA-based resin specimen was designed using CAD software and fabricated using a DLP 3D printer to specific dimensions. Characteristics, mechanical properties, and cytotoxicity levels of these designed UA-based resins were investigated and compared with a commercial 3D printing denture base acrylic resin (BB base) control group at different UV exposure times. Shore hardness-measurement data and MTT assays were analyzed using a one-way analysis of variance with Bonferroni's post hoc test, whereas viscosity, maximum strength, and modulus were analyzed using the Kruskal–Wallis test ($\alpha = 0.05$). UA-based photopolymer resins with tunable mechanical properties were successfully prepared by replacing the UA materials and the UV exposure times. After 15 min of UV exposure, the 5812 and 594 groups exhibited higher viscosities, whereas the 88A and 87A groups exhibited lower viscosities compared with the BB base group. Maximum flexural strength, flexural modulus, and Shore hardness values also revealed significant differences among materials ($p < 0.001$). Based on MTT assay results, the UA-based photopolymer resins were nontoxic. In the present study, mechanical properties of the designed photopolymer resins could be adjusted by changing the UA or UV exposure time, suggesting that aliphatic urethane acrylate has good potential for use in the design of printable resins for DLP-type 3D printing in dental applications.

Keywords: photopolymer resin; polyurethane acrylate; digital light processing; complete denture base

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1. Introduction

Complete denture prosthetics, including those made with acrylic denture base resins and artificial teeth, are among the main oral prosthetic devices used to replace a complete arch of missing teeth. Poly methyl methacrylate (PMMA) is the most commonly used resin in dentistry due to its low density, aesthetics, and cost-effectiveness [1], and can be used to fabricate a denture base through conventional processing techniques such as compression molding, fluid resin pouring, and injection molding [2]. However, maladaptation of dentures has been identified due to considerable polymerization shrinkage and feature distortion during processing [3,4].