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Digital dental models in orthodontics: A review

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Abstract

Digital 3 dimensional (3D) dental models are considered one of the most important advancements in modern dental history. Digital dental models are used in diagnosis, treatment planning, and appliance production phases in orthodontics. The present technology of digital dental models reached, and in some points, exceeded the plaster models' accuracy. The use of digital models with CBCT images and rapid prototyping techniques brought the possibility of new treatment techniques, some of which are considered as the future of modern orthodontics. This article aims to review the current use and success of digital 3D models in orthodontic practice.

Keywords: digital orthodontics, orthodontic model, orthodontic diagnosis, digital dentistry

1. Introduction

Orthodontic dental models of patient's dentitions provide important information during diagnosis, treatment planning, evaluation of treatment results and appliance production. Dental models successfully transfer the data about dental morphologies, occlusion and dental relationships, which are sometimes difficult to detect during intraoral examination (1). Impression materials and plasters were used to produce dental models for the last three centuries. Plaster models occupied a lot of storage space and providing optimal storage conditions were an important limitation for their long-term preservation (2). Today, using 3 dimensional (3D) digital technologies, dental models can be produced digitally and stored in a computer drive. Digital 3D models are considered as a revolutionary advancement in the orthodontic practice. Beside the simplicity of storing and transferring, 3D models also opened doors for new diagnosis and treatment options such as 3D planning of orthognathic surgery and clear aligner therapy, which are considered as the future of orthodontic mechanics. This article aims to review the current use and success of digital 3D models in orthodontic practice.

2. Dental 3D scanners and digital model acquisition

Although the designs for digitalization of dental models dated back to 1980's, widespread use of digital 3D models started lately. Digital models were commercially introduced in late 1990's (3). Digital scanners, printers and software technologies became more accessible with the competition in the market. Device and software development and variety allowed these systems to be more affordable as these devices became faster and more reliable. Study casts can be created with different technologies and devices. Intraoral and tabletop dental scanners are commonly used in orthodontic practice. Manual impression taking procedures either with or without stone model production procedures are still needed for the use of tabletop dental scanners. Intraoral scanners on the other hand; scans the patient's dentition directly intraorally without the need of any manual impression or plaster production.

While scanners provide superior 3D model qualities, their precision is still improving at the regions with sharp edges. Clinicians do not need micron-level sensitivity for diagnostic models in their orthodontic practices; therefore, intraoral scanners had an increasing popularity in orthodontics (4, 5). Researchers emphasized that intraoral scanning was also easily accepted by the patients and that the patients in their study preferred intraoral scanning over manual impression.

Digitally produced dental models also have the advantages of smaller size factor, ease in disinfection and cleaning, decreasing the chair time and eliminating additional laboratory work (6). The most important disadvantage of intraoral scanning when compared with model/impression scanning is that intraoral scanning must be done according to a scanning protocol and learning the protocol has a steeper learning curve; furthermore, scanners were considered costly when compared to the plaster models (7). As these technologies are getting more and more affordable, they are becoming more price efficient.

Digital dental scanners generate 3D view in their own file format but most of them can export the 3D file as an open source '*stereolithography*' (STL) format. STL format can be used universally for storage, diagnosis, treatment planning

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and appliance production. STL file format is the commonly used 3D model format in digital dentistry.

Digital models can be used virtually or can be printed with 3D printers using rapid prototyping, a group of techniques used to quickly fabricate a scale model of a physical part or assembly using three-dimensional computer aided design (CAD) data, techniques.

3. The use of 3D models in orthodontics

Digital dental models are used in diagnosis, treatment planning and appliance production in orthodontics.

4. Diagnosis

Dental study models provide valuable information for orthodontic diagnosis. Detailed inspection of the occlusal relationships and measurements of tooth and arch sizes are done on the study casts prior to orthodontic treatment.

4.1. Analysis of the occlusion

One of the drawbacks of using stone dental models as an archiving method is; if optimal storage conditions are not met, any damage or loss of dental stone models cause irreversible data loss of valuable patient information. Digital models on the other hand are reliable and can be reached easily at any point for re-evaluation. Storage of digital data is also as important; all the patient's digital data can be saved in a single usb drive. Setting systematic backup conditions is the key to prevent any data loss. With the many cloud solutions, data can be reached at any location, which improves productivity and saves both time and space. Although there were conflicting findings in the literature about the diagnostic value of digital dental models, current studies show that the digital dental models are equal to, if not exceeded, their plaster counterparts.

Santoro et al. (8) compared the overjet, overbite and tooth dimensions on plaster and digital models. They found that although there were statistical differences between plaster models, which was considered as the "golden standard", and digital models, the differences (0.16 to 0.49 millimeters) were minimal and were not clinically significant.

Mayers et al. (9) showed that Peer Assessment Rating (PAR) scores could be successfully derived from digital models.

Several other studies showed minor but statistically significant differences in occlusal contacts, overjet, bucco-lingual inclinations, alignment, and total American Board of Orthodontics (ABO) grade scores between the plaster and digital models (10, 11).

More recent studies concluded that there were no significant differences in diagnostic capabilities of plaster and digital dental models and that the digital models could be reliably used to observe the occlusal relationships (9, 12, 13). Different software algorithms and techniques might have been the cause of these differences. Advances in the technologies of modern intraoral scanners, are making them more reliable and precise every other day.

4.2. Arch length and tooth width

Calibrating rulers and references were used in 2D photographic and radiographic analysis. With the advances in digital models, 3D dental models are precalibrated and many measurements, such as arch length, tooth size discrepancies etc. can be done manually or automatically with a variety of software. With the help of dental software, different model analysis, like Bolton discrepancy, crowding analysis, intercanine width etc. can be completed much faster than manual methods. Clinicians spend less time on preparation for diagnosis, which leaves more time for the actual treatment planning.

Digital 3D models obtained with intraoral scanners were compared to digital models obtained with CBCT (Cone beam computer tomography) and plaster models in the previous literature. Most of these studies showed that intraoral scanners provided superior reliability than CBCT images and similar results with plaster models, especially for linear measurement made on two landmarks (14,15).

Differences in Bolton index calculation between plaster models and digital models obtained from CBCT image was studied by (16). The authors concluded that even CBCT images, which was shown inferior to intraoral scanning in current literature, was comparable with plaster models in Bolton index calculation.

Few relatively older studies report statistically significant but clinically irrelevant differences between digital models and plaster models in arch length and space measurements (17, 18). Erdinc et al. (19) found significant differences in mesio-distal widths of molar and premolar teeth and in total arch lengths between the measurements made on digital and plaster dental models, but they also emphasized that these findings were clinically acceptable. These are due to the lack of precise scanners and software, which were developed after these studies. Naidu and Freer (20) expressed that the mean differences in anterior and overall Bolton ratio between digital models and plaster models were below 1 millimeter, and that 95% of the errors were in a clinically insignificant range. Koretsi et al. (21) showed that digital workflow for orthodontic model analysis is more reliable than traditional manual plaster model analysis.

5. Treatment planning

Digital dental models brought various treatment applications into the field of orthodontics. Digital setups, visualization of treatment results, quality assessment of treatments, 3D analysis of the tooth movement, and Computer Aided Design and Manufacture (CAD-CAM) of the orthodontic appliances are among the examples of current digital applications. Digital models combined with 3D CBCT images and 3D facial scanning data already exceeded the conventional orthodontic and orthognathic planning techniques.

Digital 3D technology brought the possibility to communicate with the patient over their own models and made it possible for patients, to see and discuss proposed treatment plans using 3D setups and forecasted scenarios, before getting into the surgery room.

5.1. Model setup

Advanced 3D technology enabled the users to merge and calibrate multiple 3D images, which were acquired from different sources. The development of a 3D setup that displayed individual crowns, roots and craniofacial structures helped the clinicians in treatment planning to determine various treatment options, monitor changes over time, predict and display final treatment results and measure treatment outcomes accurately.

Macchi et al. (22) separated roots from craniofacial CBCT data and superimposed laser scanned 3D dental model data on extracted 3D root images to form a digital 3D dentoalveolar complex. The researchers then simulated premolar extraction therapy by eliminating first premolars to observe the possible final positions of the teeth and their relationship with the surrounding structures. Im et al. (23) asserted that plaster model setups and virtual setups of digital models lead to similar measurements. Barreto et al. (24) compared the reliability of digital model setups with plaster setups and post-treatment dental models of the patients and concluded that digital setups were as accurate and effective as the plaster setups and constituted a tool for treatment planning, which could be reliably reproduced in orthodontic treatments. Eliminating the additional laboratory work has been an important advantage of digital setups.

5.2. Digital orthognathic surgery planning

Cone beam computer tomography (CBCT) images, digital dental models and stereophotogrammetry images are superimposed to form a “virtual patient” for digital orthognathic surgery planning. This made it possible to eliminate most of the time-consuming conventional model surgery steps including the facebow transfer. Digital planning consists of two phases: osteotomy and wafer production. Digital models obtained with either model or intraoral scanning provide superior data of the teeth registered in occlusion, which are used in the planning phase (25).

Cousley et al. (26) confirmed that digital surgical planning and wafer production techniques achieved level of accuracy, that match the conventional facebow and model surgery. De Riu et al. (27) reported that digital planning was even more successful than conventional planning for the orthognathic correction of facial asymmetry. Chen et al. (28) reviewed the literature on comparison between virtual surgical planning and traditional surgical planning. They concluded that VSP technique has become a good alternative to TSP technique for orthognathic surgery.

5.3. Smile design

Mentality of orthodontic treatment planning shifted towards analyzing the smile aesthetics and soft tissue in the last two decades. Although smile analysis is not a new term for orthodontics, utilization of digital technology for forecasting the effects of the treatment plan on smile aesthetics is currently a popular trend. “Smile design” concept was acquired from aesthetic dentistry and its extensive use in orthodontics started a few years ago. Smile design technique is especially useful for the treatments when multidisciplinary approach is needed, like the orthodontic-restorative treatment of tooth shape anomalies. The technique depended on superimposing the photo of dentition after possible treatment over patients own smile photo, so that the possible effects of the treatment on the smile could be inspected. Frontal photographs were used for smile design and only one dimension could be seen during the planning (29, 30).

Digital models and stereophotogrammetry enabled superimposition of dental models inside 3D facial surface image, so that the effects of the treatment on smile could be analyzed three dimensionally.

The final 3D design (in STL format) can be exported to a 3D printer to generate the physical model of the new design. This model can be used to fabricate a matrix for a mock-up and provisional and guides for tooth preparation, crown lengthening, and implant placement can be produced. It can be integrated into treatments with digitally planned setups like clear aligner therapy. Digital smile design protocol made diagnosis more efficient, and treatment plans more consistent. It provides more logical and straightforward treatment sequences, reducing the risks and improving the results (30).

6. Appliance design and fabrication

High precision 3D printing technology is being used to produce variable orthodontic appliances like retainers, removable appliances, indirect bracket placement trays and occlusal splints (31, 32). Three-dimensional design and printing can be used to produce clear retainers for home bleaching (33). Today, one of the most important use of 3D printing technology is the production of clear aligners.

There are specific software programs on the market which allowed individual bracket and aligner designs. Even complicated appliances like Herbst and sleep apnea appliances can be digitally designed and fabricated to accurately fit the dentition (34).

Material technology plays an important factor in these advances in digital appliance design. Materials with more suitable characteristics and development of user-friendly design tools lead to the in-office production of orthodontic appliances, which is an important step towards individual appliance design and manufacture. Like its advantages in diagnosis and treatment planning, digital technology reduced the steps in orthodontic appliance workflow and eliminated the need of additional, and sometimes non-standard, laboratory procedures.

6.1. Clear aligners

In 1998 Align Technology Inc. released Invisalign, the first clear aligner method, which used digital models to build the appliances. Modern production of clear aligners depends on setup of digital 3D dental models and plans of incremental stages for specific tooth movements with different software. Various possible treatment options can be visualized on digital setups. The clinician can see and interfere with the treatment plan in sophisticated software programs (35). After the clinician's approval of the proposed plan, incremental movements can be used to 3D print dental models for each increment then, thermoform aligner materials can be used such as polyamide (36).

Although the indications of digitally produced clear aligners were limited at the beginning, with development of material, computer technology and clinical research, the indications of clear aligners have been greatly extended. There are plenty of studies that showed successful cases treated with clear aligners, that show how these aligners can treat various types of cases from mild to severe malocclusions (37) Digital 3D technologies played an important role not only in design and production; but addition of artificial intelligence (AI) into the equation showed very promising improvements in orthodontic treatments and AI is also used in the analysis of treatment effectiveness. Clear aligner therapy even has some advantages over fixed orthodontic treatment. Khosravi et al. (38) reported that clear aligner therapy especially managed vertical dimension relatively well and Ke et al. (37) asserted that clear aligner therapy had the advantages possibility of segmented tooth movements and shortened treatment durations.

6.2. Digital orthodontic laboratory work

Studies on automation of fabrication of orthodontic removable appliances date back to 1990's. The advancement was visible after the commercial use of digital 3D models. Digital models facilitated effortless transfer of data via digital mediums. With the widespread use of 3D printing, orthodontic laboratories started using digital models and appliance design software.

There are two different workflows for digital removable appliance fabrication. First method is that laboratories 3D prints the study models and build the appliances with conventional techniques. Fabricated appliances are then sent to the clinics. This method eliminates the time needed for impressions, plaster model preparations and transfer of the study models.

The second method of appliance fabrication is gaining popularity. In which, digital models are sent to the laboratory, appliances are designed virtually, and designs are sent back to the clinic in printable STL formats via digital mediums. The clinicians can either 3D print the appliance in-office or can send the STL file to a 3D printing center to be printed. Directly in-office printing the appliance, eliminates the need to build plaster or digital models and the time needed for the transfers (39).

Several researchers successfully fabricated all parts of a removable appliances, which were consisted of metal clasps and resin base plates with the help of 3D printers (40, 41).

Commercialization of metal 3D printers enabled the fabrication of complex metal devices. Graf et al. (42) applied a miniscrew supported expansion device, which was designed and produced with the aid of computer aided design and 3D printing technologies. It is now possible for the clinicians to have the appliances designed in another part of the world and receive the design by e-mail in a matter of days.

6.3. Customized orthodontic brackets

Lingual orthodontic brackets are one of the most aesthetic appliances currently in use, because they are placed on the lingual surfaces of the teeth. Because lingual morphology is quite variable standard bracket bases, like the ones in conventional labial brackets, are not preferable to be used in the lingual surface of teeth. Time consuming laboratory process was needed for model setup and preparation of individual composite bases, which also made the lingual brackets rather bulky.

Modern lingual bracket systems utilize digital dental models to virtually design customized base for every tooth. The brackets are manufactured using 3D printing processes (43). The customized bracket system was found so successful that it was adapted to labial bracket fabrication. When coupled with custom formed arch-wires, customized bracket systems were able to overcome the difficulties of different tooth morphologies and increase the efficiency of the treatment (44, 45).

6.4. Digital indirect bonding

Orthodontic brackets are commonly bonded on the teeth directly by the practitioner. Indirect bonding technique was developed to overcome the bracket positioning errors due to limited view of the teeth during direct bonding. Brackets were placed on their pre-planned positions on plaster casts and were transferred to patient's mouth with custom made transfer trays.

Digital version of indirect bonding eliminated the need for complex laboratory and clinical processes. There are currently three different ways for digital indirect bonding.

Like appliance production, the most basic way of incorporating digital technology to indirect bonding is; 3D printing the study models and applying conventional indirect bonding steps which were normally applied on plaster models.

Second method includes using of software individually designed for indirect bonding. Brackets are virtually placed on digital models in the software. Some of the programs can apply basic set-up on the dental models to show a forecast of possible treatment options. Users can choose from the 3D data of the brackets which are stored in the software's own library. Digital study models with placed brackets can be 3D printed to fabricate the transfer trays from silicone or thermoform materials in the laboratory. Real brackets are then placed in the grooves on the transfer tray.

Thirdly, the users can finish all the above workflow digitally including the design of the transfer trays. The trays are 3D printed with a flexible resin and brackets are placed in their grooves (46).

Using digital setups during the digital planning of bracket positions, were shown to increase the precision in positioning (47).

Although digital indirect bonding technology is promising in decreasing chair time and laboratory steps, there are some concerns about high error rate of the system (48). Kim et al. (49) reported positioning errors were more frequent in posterior teeth and that the technique should be carefully used.

One of the main disadvantages of the system is that the user is limited by the types of bracket models that are stored in the software's library.

6.5. Miniscrew insertion guides

Miniscrew anchorage significantly reduced the need for patient compliance and allowed many advancements of orthodontic treatment mechanics. Manual insertion of miniscrews increased the risk of complications; therefore, surgical insertion guides can be used for precise positioning of the screws.

Digital insertion guides which use CBCT data and digital dental models were transferred from implant dentistry. The most important advantage of using CBCT images is being able to superimpose the 3D image of the roots, this enables the user to plan according to true 3D morphology (50).

Digital guides can be used for both buccal and palatal insertion fields and were found to greatly reduce the risk of root damage when compared with the direct manual placement method for insertion (50, 51).

7. Conclusion

Present technology of digital dental models reached, and in some points exceeded, the plaster models in accuracy. Use of digital models with CBCT and rapid prototyping techniques brought the possibility of new treatment techniques, some of which are the future of modern orthodontics. Studies reported minor differences between digital and plaster models which are not clinically relevant. Digital 3D models and technologies provide important advantages in orthodontics from diagnosis to treatment. These advances changed the orthodontic workflow significantly, soon today's innovations might be considered as the new "golden standard".

Conflict of interest

None to declare.

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