Republic of Iraq
Ministry of Higher Education
and Scientific Research
University of Baghdad
College of Dentistry

Digital Orthodontics

A Project

Submitted to the College of Dentistry,

University of Baghdad, Department of Orthodontics

in Partial Fulfillment for the

Bachelor of Dental Surgery

By

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April, 2022

Certification of the Supervisor

I certify that this project entitled "Digital orthodontics" was prepared by Manar Adnan Mohammed

under my Supervision at the College of Dentistry/University of Baghdad in partial fulfilment of the graduation requirements for the Bachelor Degree in Dentistry.

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Date:

Dedication

I would like to dedicate my humble effort to my sweet and lovely **Father and Mother.** Their affections, love, encoragement and prays, day and night, helped me succeed.

Manar Adnan Mohammed

Acknowledgement

First and foremost, praises and thanks to **Allah** Almighty for helping me fulfill my dream, for his blessings throughout my work to complete it successfully.

I would like to extend my deepest respect and gratitude to the Dean of College of Dentistry, University of Baghdad, **Prof. Dr. Raghad Al-Hashimi**.

My sincere thanks to Assist. **Prof. Dr. Yassir A. Yassir**, Head of Orthodontics Department, and all professors and seniors in the department for them pleasant cooperation.

I would like to show my deep and sincere gratitude to my research supervisor, Prof. Dr. **Ali AL_Bustani** for his advice, encouragement, and guidance in planning and conducting this project.

Table of contents

List of Figures

List of Abbreviations

subject	Abbreviations
CAD-CAM	**CAD stands for Computer-Aided Design and CAM stands for Computer-Aided Manufacturing,**
CAT	**clear aligner Therapy**
CBCT	**Cone-beam computed tomography**
CT	**computerized tomography**
CU NITI	**Copper Nickel-Titanium**
2-D	**2-dimensional**
3-D	**3-dimensional**
FOV	**Field of view**
FFF	**fused filament fabrication**
LNT	**linear non-threshold**
NITI	**Nickel-Titanium**
PVS	**polyvinyl siloxane impression material (PVS)**
SL	**self-ligating brackets**
SLM	**selective laser melting**
SLS	**selective laser sintering**
STL	**Stereolithography**
TMA	**Titanium molybdenum alloy**

Introduction

Orthodontics is now approaching its fourth revolution since its inception as a specialty of dentistry in the early 1900s. In those days, malocclusion was treated with the application of metal rings cemented to teeth to support wires for applying moving forces. Later in the 1960s, the rings were substituted by the first brackets to support wires made from stainless steel, then conventional brackets made of transparent or translucent non-metallic material were introduced in the early 1970s **(Tartaglia *et al.*, 2021).**

Orthodontics, like the other dentistry disciplines, has recently benefited from the influx of technological innovations. These innovations have principally involved the means and procedures of diagnosis, with new developments being introduced in the field of photography, tomography, optical and laser scanning **(Perri *et al.*, 2014).** Several orthodontic systems implement these new technologies, providing the orthodontist with a comprehensive orthodontic treatment package consisting of digital diagnostics, 3-dimensional (3D) digital planning, and computer-designed customized brackets and arch wires **(Penning *et al.*, 2017).**

Customized orthodontic treatment systems rely on digital models of the patient's occlusion, which are generated from accurate impressions taken before treatment, scans of the dental arches, scans of the plaster casts, or CBCT acquisition **(Grauer *et al.*, 2012).** A virtual setup of the desired outcome is then derived. This setup serves as a three-dimensional (3D) interactive treatment planning tool and is used for the production of personalized appliances (archwires, brackets, and indirect bonding transfer devices) **(Perri *et al.*, 2014).**

One such system is the Insignia (ORMCO Corporation) system, which entered the market several years ago and is one of the most advanced computerized systems for obtaining personalized appliances for patients **(Gracco *et al.*, 2013).** With the recent increase in adults seeking orthodontic treatment, there has been a corresponding increase in demand for appliances that are both more aesthetic and more comfortable than conventional fixed appliances. The term Clear Aligner Therapy (CAT) embraces a wide range of appliances with differing modes of action, methods of construction, and applicability to various malocclusion treatments **(Weir, 2017).** However, there are some limitations such as it depends on patient compliance which is a crucial factor to achieve the designed tooth movement. Alteration of tooth morphology can result in unfitted aligners, thus re-scanning or PVS impression is required. In addition, posterior open bite is a common side effect of clear aligner therapy**(Kanpittaya *et al.*, 2021).**

Aims of the study

1. To review and highlight the contribution of contemporary digital orthodontic techniques in the success of orthodontic treatment.
2. To evaluate the range of malocclusions that could be addressed with digitally driven orthodontic systems.

Chapter one: review of literature

1.1 Tools used in digital orthodontics

1.1.1 Digital Diagnosis

Orthodontics and dentofacial orthopaedics is one of the most complex branches of dentistry that requires a careful interpretation of a large amount of information to attain a correct diagnosis and treatment planning. Similar to a wax setup, the digital setup is a tool that helps with treatment planning and it is up to the creator of the setup to respect the biologic limitations of tooth movement and mimic realistic biomechanics **(Im *et al.*, 2014).** Barretoa et al. reported that the creation of a digital setup is much faster than creating a wax setup due to the lab work required when working with plaster **(Barreto *et al.*, 2016).** Working with digital setups offers many advantages such as relatively time saving, the ability to superimpose the setup with the original models, determining the precise amount of movement for each tooth, and it can be instantly stored and shared with others easily **(Reshmi and Naveen, 2021).**

1.1.2 Digital Study Models

Plaster study models were the "gold standard" in orthodontic diagnosis and treatment planning **(Han *et al.*, 1991).** Later advances brought about more dimensionally stable impression materials than wax and alginate, such as elastic polyether and polyvinyl siloxane **(Peluso *et al.*, 2004)**. Study models provide a three-dimensional view of a patient's occlusion and are more amenable to routine measurements like tooth size, arch length, arch width, overjet, overbite, midline discrepancy, curve of Spee, etc **(Reshmi and Naveen, 2021).** However, it has disadvantages like lack of tactile input, time required to learn how to utilize the system so if it does not done accurately it will need extra time to repeat it, scarcity of digital model supplier companies, questions surrounding the accuracy of digital models and additional costs **(Sharma *et al* ., 2015).**

On the other hand, the concept of three dimensional (3D) virtual orthodontic models seems very favorable in eliminating the problems of conventional plaster models, and simplifying the practice management and communication between different specialties. Virtual study models (e.g. Ortho Cad™) made their first appearance on the orthodontic market in 1999 **(Tomassetti *et al*., 2001).** The startup software for OrthoCAD™ is free of charge, OrthoCAD's 3-D browser software allows the clinician five simultaneous views of the models. This enables the models to be viewed from multiple perspectives at the same time, also OrthoCAD™ also features a cross-sectioning tool that can slice the digital models in any vertical or horizontal plane to check symmetry, overjet, overbite or to measure any location **(Peluso *et al.*, 2004).**

Shape Ortho System is a recently introduced 3-D representation of a patient's dentition on the computer screen. The system utilizes a propertied laser scanner (R700) that projects a laser line onto the surface of the model or impression, a 3-axis motion system and two high resolution charge-coupled-device cameras, one on either side of the laser that observes the profile of the line as it falls on the object. The two-camera system reduces scanning time because less reorientation of the model is required to capture surface details that would be missed by a single camera due to shadowing **(Barry *et al*., 2011)**.

1.1.3 Digital Photographs

The digital single lens reflex cameras were verified for use in intra and extra-oral photography and proved to produce perfect images when used with the recommended macro-lens and macro-flash techniques. Digital photography was introduced to evaluate facial harmony. It allows clinicians to establish a more proportional focus on all three structures of the triad to assess patient's deformity **(Charkhandeh *et al* ., 2017).**

1.1.4 CBCT

Cone-beam computed tomography (CBCT) is a radiographic technique introduced to the United States dental market in 2001. CBCT technology uses a cone-shaped source of ionizing radiation and a two-dimensional detector **(De Vos *et al*., 2009).** CBCT has concerned significant attention from practitioners who seek to enhance diagnosis and treatment for their patients. However, risks and limitations need to be explored and weighed against the benefits of CBCT in each case **(Leonardi, 2019).**

Theoretically, any amount of ionizing radiation, no matter how small, has the potential to cause a harmful effect (**Hall and Giaccia., 2006).** Radiation is a carcinogen, and current radiation protection protocols are based upon the linear non-threshold (LNT) assumption that even very low doses of radiation can cause cancer **(Buttke and Proffit, 1999).** The problem in orthodontics is that most patients who undergo orthodontic therapy are children and adolescents, being more radio-sensitive and susceptible to the untoward effects of ionizing radiation than adults **(Bulas *et al*., 2009).** Because the dose received is strongly related to the field size, a small field of view (FOV) can be selected for the region of interest that triggers the interest in CBCT acquisition **(Kapila *et al*., 2011).** In order to improve the use of CBCT, the FOV should be justifiable, patient-specific, and indication-oriented **(Oenning *et al.*, 2018).**

The effective dose of a digital panoramic radiograph has the range of 6–38 micro-Sieverts **Ludlow *et al*. (2006)** and the effective dose of a cephalometric radiograph has the range of 2–10 Sv, while the range of effective doses of CBCT is very large and has been reported to be 5.3–1025 Sv, depending on the size of FOV, specific technique factors, and the machine itself **(Theodorakou *et al.*, 2012).**

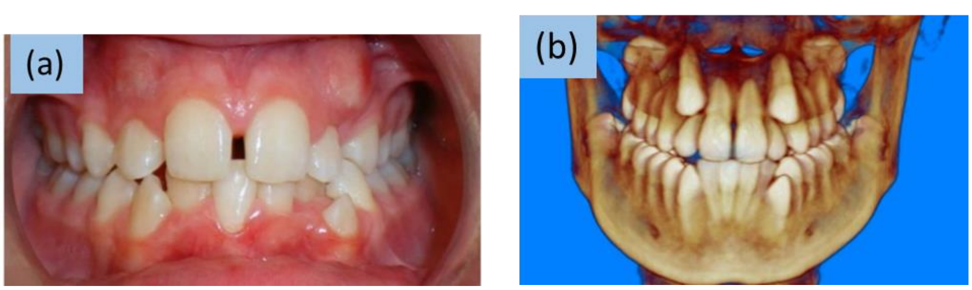
Further to the exposure to ionizing radiation, CBCT comes with other restrictions and concerns. For example, CBCT scanners have higher cost and limited accessibility when compared to conventional radiographic imaging techniques. In addition, CBCT images are adequate for visualization of teeth and bone, but are unable to represent the internal structure of soft tissues or soft tissue lesions with high accuracy **(Weiss and Read-Fuller, 2019).** One of the artifacts that happen with CBCT are metal artifacts. In orthodontics, these artifacts can be noted on the images around orthodontic brackets and bands (scattering), **Hirschinger *et al.*(2015)**display noise, cupping artifacts and motion artifacts, especially in young orthodontic patients who are more likely to move during long CBCT scans **(Coşkun and Kaya, 2018).**

The great advantage of CBCT is that it provides images of various dental, oral, and maxillofacial structures in multiple orthogonal images (i.e., coronal, sagittal, and axial sections) **(American *et al.*, 2012).** The use of CBCT must be justified if conventional imaging techniques such as panoramic and cephalometric radiographs fail to provide correct diagnosis or when CBCT has a positive effect on treatment options or treatment optimization **(Chinem *et al.*, 2016).** For example, the American Dental Association recommended that CBCT be decided only when there is an expected diagnostic benefit for the patient or significant improvement in the clinical outcome **(American *et al.*, 2012).** The British Orthodontic Society guidelines are comparable, and did not recommend CBCT imaging for all orthodontic patients **(Isaacson *et al*., 2015).**

CBCT provides information on impactions and ectopic teeth eruption, the stage of dental development, position and size of the tooth or follicle, evaluation and detection of any supernumerary teeth. CBCT can be used in craniofacial orthodontics in which effects of maxillary expansion, evaluation of the clefts, and the skeletal and soft tissues can be evaluated in all dimensions **(Liu *et al.*, 2007)**. If temporary anchorage devices such as mini-implants or mini-plates are planned before or during orthodontic treatment, CBCT can help the orthodontist in evaluating the planned site for insertion or the status of the temporary anchorage device after the insertion **(Kim *et al*., 2007)**. One of the great features of CBCT is its ability to construct different views, such as a panoramic view of the teeth and adjacent structures and another cephalometric view. Therefore, if a large volume CBCT is made, these views can be generally made without taking additional 2D panoramic and cephalometric radiographs **(Farman and Scarfe, 2006).**

The following orthodontic cases provide examples where CBCT was used for diagnosis and treatment planning to obtain information not possible through conventional 2D imaging.

1- Evaluation of impacted teeth (Figure 1)



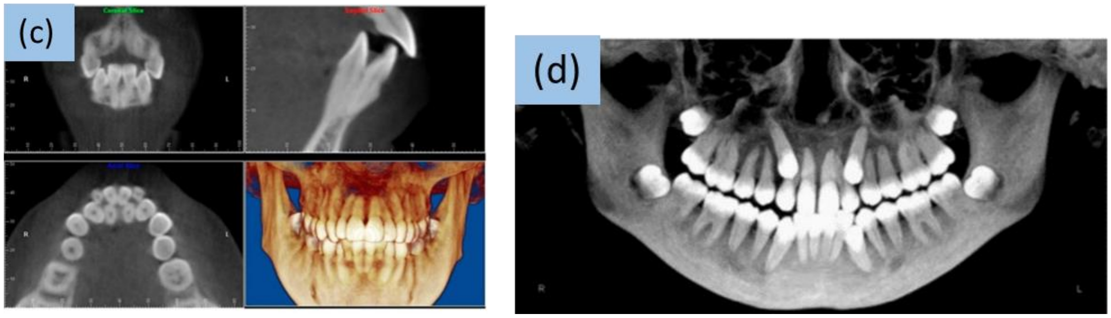


Figure 1. Evaluation of impacted teeth (a) Intraoral photograph of a case with impacted maxillary canines.(b) CBCT volume rendering.(c) Coronal, sagittal, axial and volume rendering views.(d) Maximum intensity projection **(Reshmi and Naveen, 2021**).

2- Evaluation of buccal and lingual cortical plates (Figure 2)

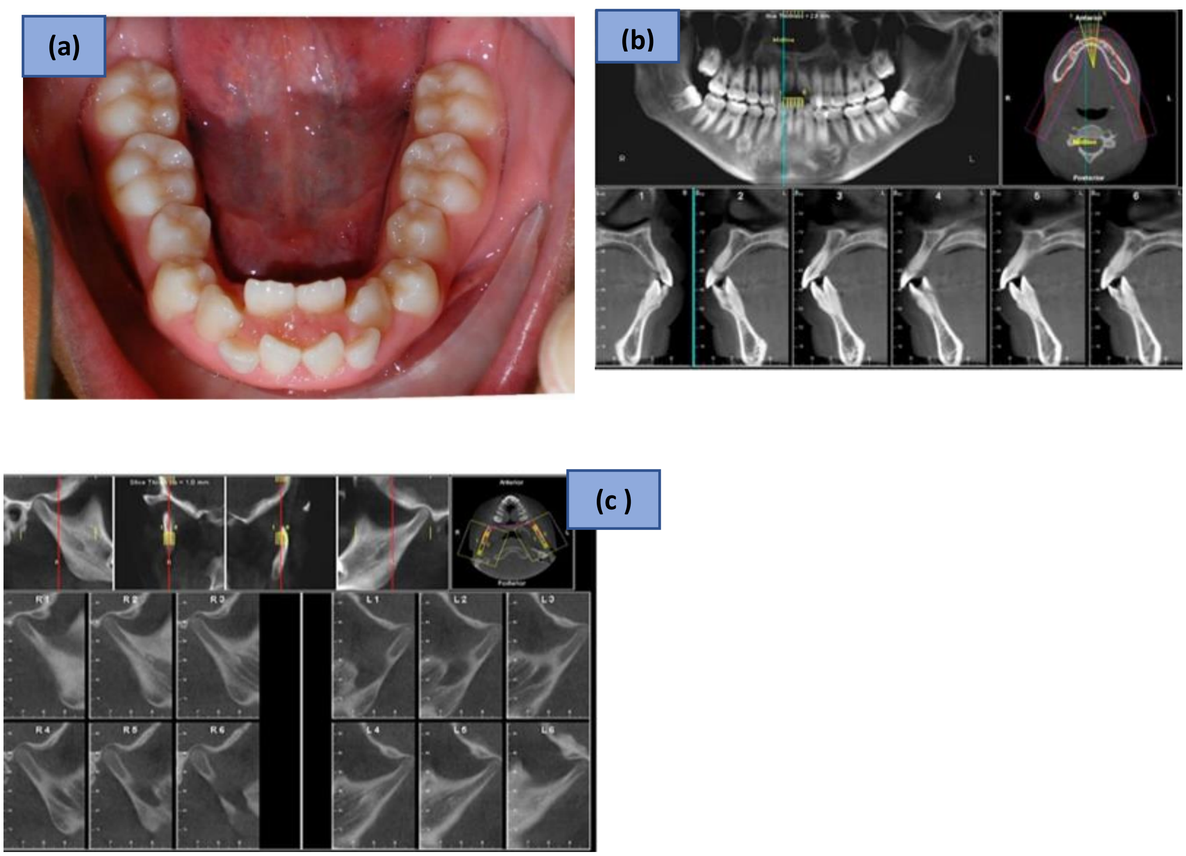


Figure.2 Evaluation of buccal and lingual cortical plates (a) crowding of mandibular teeth. (b) panoramic axial and six cross-sectional. (c) coronal, sagittal, axial views and volume rendering views **(Reshmi and Naveen, 2021**)

3-Assessment of an impacted maxillary canine located superior to a first premolar. (Figure 3**)**

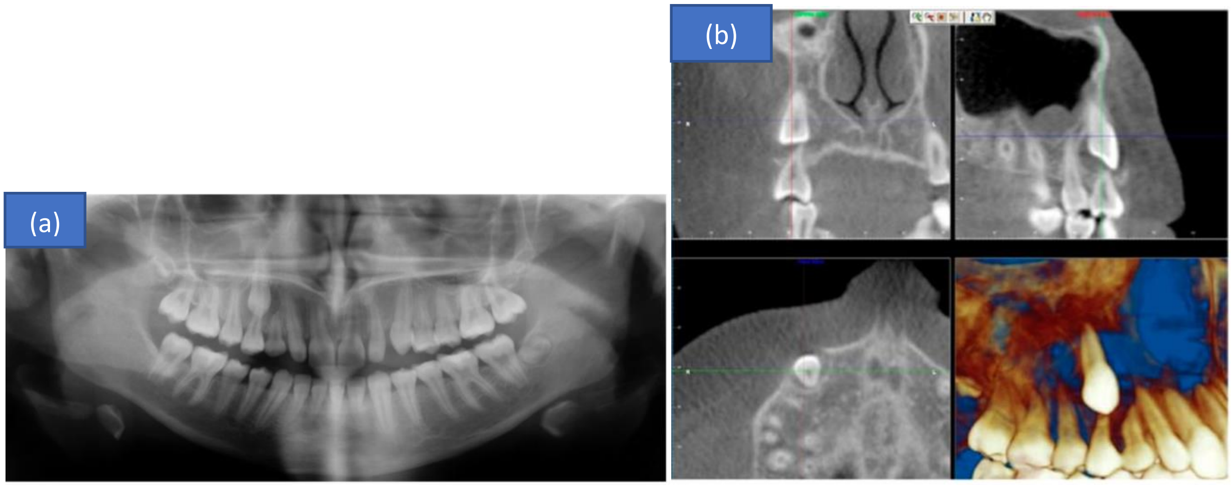


Figure 3. Assessment of an impacted maxillary canine located superior to a first premolar (a) A conventional 2D panoramic radiograph that did not depict accurate status of the canine and first premolar. (b) Coronal, sagittal, axial views, and volume rendering showing the impacted canine and its relationship to adjacent structures**(Reshmi and Naveen, 2021**)

4-Assessment of an impacted canine with close proximity to the lateral incisor (Figure 4)

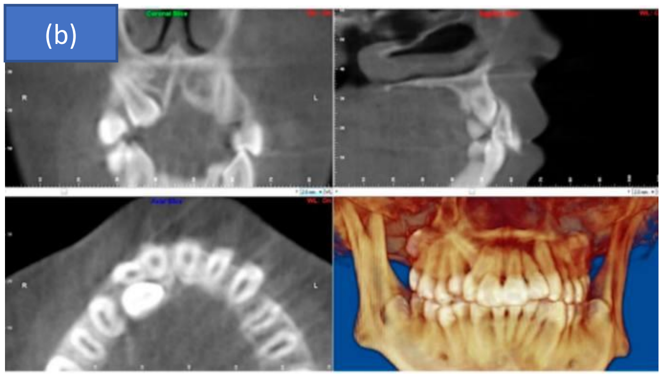


Figure 4. Assessment of an impacted canine with close proximity to the lateral incisor (a) Photographs and 2D panoramic radiograph of a case with an impacted maxillary right canine. (b) Coronal, sagittal, axial views, and volume rending, showing significant information about the location of the impacted maxillary right canine**(Reshmi and Naveen, 2021**).

1.2 Goals in digital orthodotics

A major goal of orthodontics is establishment and maintenance of an appropriate arch form for each patient, and the treatment goals should be defined during dignosis and treatment plan steps (**Grauer, 2021)**. According to the reserch, the mandibular arch form should not be modified to a major extent, and that teeth should be positioned within the zone of equilibrium between the internal and external forces **(McNamara *et al*., 2010).** Important outlines to be considered:

1- The use of non-customized orthodontics with preformed arch wires does not allow for maintenance of the arch form, especially using the prefabricated NiTi wires. A solution to this problem can be the use of setup-driven, manufactured orthodontic appliances where the initial arch shape is incorporated into the design of the brackets and wires **(Beers *et al*., 2003).** (Figure 5**).**

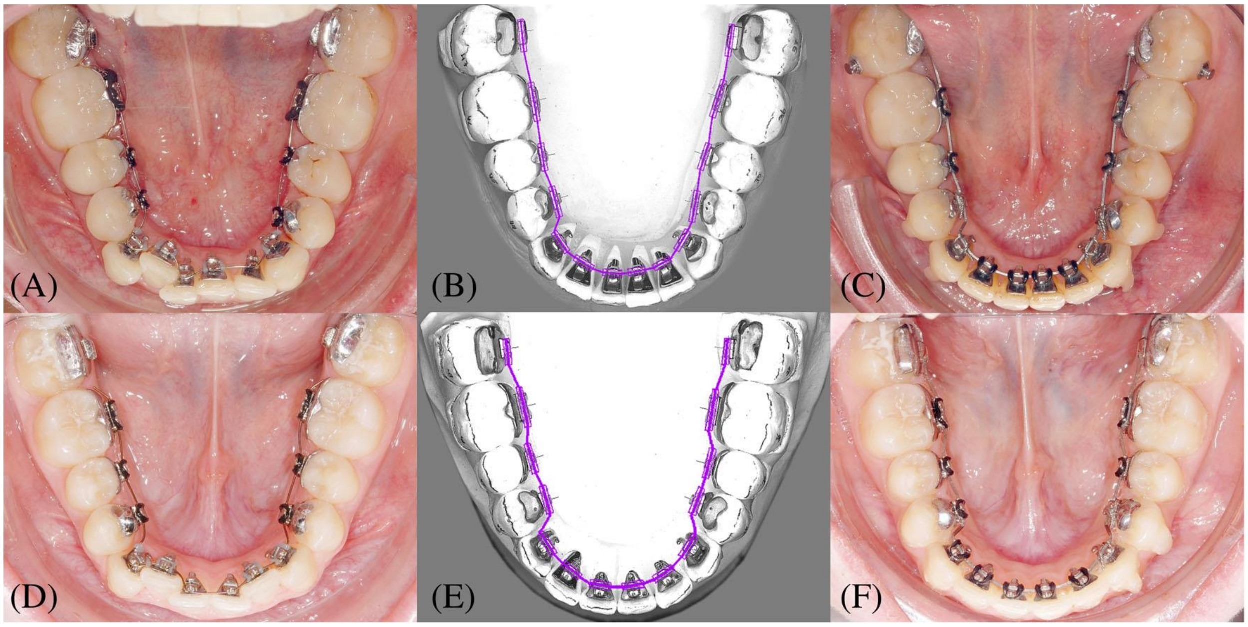


Figure 5. Arch form of Two patients (A) to (C) and (D) to (F) with similar crowding pattern and different initial arch form were treated with WIN lingual (A) and (D). The original arch form was incorporated into the setup in order to be maintained during orthodontic treatment (B) and (E). At the last appointment before debonding the crowding was resolved and the original arch form was preserved. This level of customization is not possible with preformed arch wires .(**Grauer, 2021)**

2- A second area where goals are often under-achieved is the expression of torque or inclination of the upper incisors and canines. This is due to the use of undersized wires in slots that often are oversizedand. Custimized digital orthodontics can provide specific slot dimensions for optimal torque and inclination achievements **(Schlosser *et al*., 2005)**.

3- Goal-driven orthodontics is achieved most effectively by a proactive process of design and manufacturing of orthodontic appliances where the target tooth positions are planned on a dental setup. The setup includes both intra-arch and inter-arch tooth positioning. In other words, the position of each individual tooth in relation to its neighbors is defined in the three-dimensional space; then it is refined based on the desired occlusion **(Grauer, 2021)**.

4- The amount of tooth displacement, rotation and overall expansion can be quantified and adjusted during appliance fabrication **(Jheon *et al.*, 2017).**

1.3 Advantages of digital orthodontics

1- Accurate tooth positioning, less human error during indirect bracket bonding, and the possibility of maintaining the pre-treatment arch form **(Joiner, 2010) (**Figure 6).

2- Secondary advantages can be faster treatment, with less secondary effects that are time-dependent and more accurate and precise outcomes **(Knösel *et al.*, 2014).**

Figure 6. Advantages of digital orthodontics. Small changes in angulation as seen in the lower right first molar can have a significant adverse effect on occlusion in all three planes of space—especially in the vertical dimension. In crowded situations the angulation discrepancy may not be perceptible until late in treatment. The use of customized and indirectly bonded braces minimizes errors in bracket positioning **(Grauer, 2021)**.

1.4 Insignia system

Orthodontics, like the other dentistry disciplines, has recently benefited from the influx of technological revolution. Innovative systems able to construct orthodontic appliances customized for the patients have been introduced to the market **(Perri *et al.*, 2014).** Technologic advances in photography, digital scanning, and cone beam computed tomography (CBCT) have greatly improved the diagnostic and treatment planning procedures in orthodontics. Correspondingly, the application of computer-aided design and manufacturing technologies has allowed manufacturers to produce orthodontic appliances tailored to the specific tooth shape of the individual patient; i.e, customized orthodontic appliances **(Grauer *et al.*, 2012).**

The Insignia System (Ormco, Glendora, Calif.) is one of the most advanced computerized systems for obtaining personalized appliances for patients **(Gracco *et al.*, 2013).** By using this system, the orthodontist takes impressions of the dentition with a polyvinyl siloxane impression material (PVS) and sends them to the manufacturer. Impressions are digitalized and uploaded into the software program, and the orthodontist can upload more information, including intra- and extraoral photos and x-rays. The system enables optimization of treatment results with computer-aided smile design **(Penning *et al.*, 2017).** Theoretically, individualized orthodontic treatment systems offer several advantages for both the patient and orthodontist, including better treatment results, shorter treatment duration, and less chair time **(Alford *et al.*, 2011).**

With fixed appliances, tooth movement occurs as a result of the engagement of the wire in the bracket slot. A system of forces and moments is generated and is transmitted to the tooth and its surrounding periodontal ligament. There are three customization approaches to generate a theoretical ideal force system and produce the desired tooth displacement **(Grauer *et al.*, 2012).**

1. Individualized arch wire
2. Individualized bracket slot/bracket base
3. A combination of the first two approaches

Because of individual variations in the contours of the teeth, no appliance prescription can be optimal for all patients, and compensatory bends in finishing archwires often are necessary. Custom brackets for the facial surface of teeth offer the prospect of eliminating almost all archwire bending. The Insignia system uses custom brackets on each tooth, focusing on eliminating wire bending to make the appliance more time-efficient for the practitioner and patient **(Proffit *et al.*, 2019).**

The first phase involves the collection of diagnostic information. In addition to extra- and intraoral photographs of the patient, it is necessary to gather very precise information regarding the patient's occlusion and the coronal morphology of their teeth. Some systems require that this information be acquired by means of precision impressions, while others rely on intra-oral scans of the teeth or volumetric tomography of the dental arches **(Perri *et al.*, 2014)**. For custom-designed orthodontics, the approach is to send precise polyvinyl siloxane impressions as well as photographic and radiographic information to the manufacturer. An accurate scanning of the plaster casts or CT scanning of the impressions is performed by the technicians, thus producing a digital model with 3D representation of the dental arches **(Gracco *et al.*, 2013)**. Alternatively, a 3-D scan of the dentition is taken to produce an STL file (now the most frequent input). Whatever the source, the virtual teeth need to be accurate to least 50-micron resolution to produce a virtual setup of the desired final tooth positions and archwire shapes are derived **(Proffit *et al.*, 2019).**

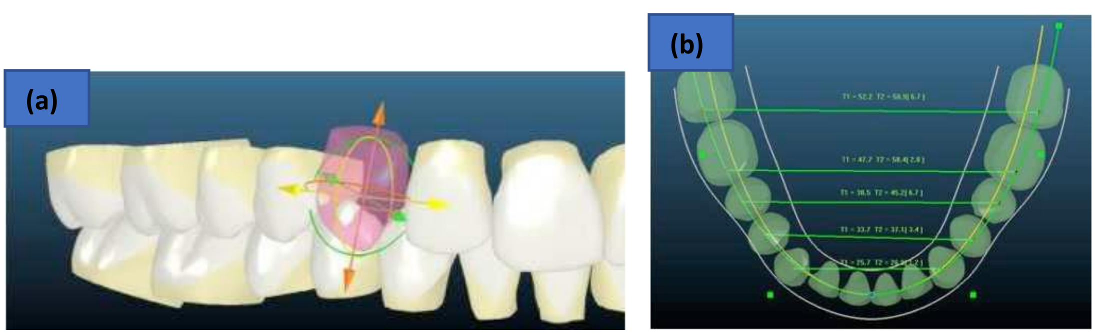
To make adjustments to the proposed initial occlusal setup and archwire shape via the online interface **(Gracco *et al.*, 2013)**:

1. 3D control of tooth placement (torque, tip, in/out, intrusion, and extrusion)

(Figure 7a).

2. Control of the arch form within the patient-specific biologic limits based on the buccal and lingual limits of the alveolar bone (figure 7b).
3. Alteration of the smile arc (figure 7c).
4. Alteration of the dental contacts in the final centric occlusion (figure 7d).

The second phase of these systems involves the use of the developed data on the patient's teeth and occlusion for digital replication of the dental arcades using reverse engineering processes. This consents acquisition of digital models of the arches, in which each tooth is defined as a CAD-CAM object, whose position can therefore be altered in three-dimensional space for virtual simulation of an ideal occlusion **(Perri *et al.*, 2014)**.



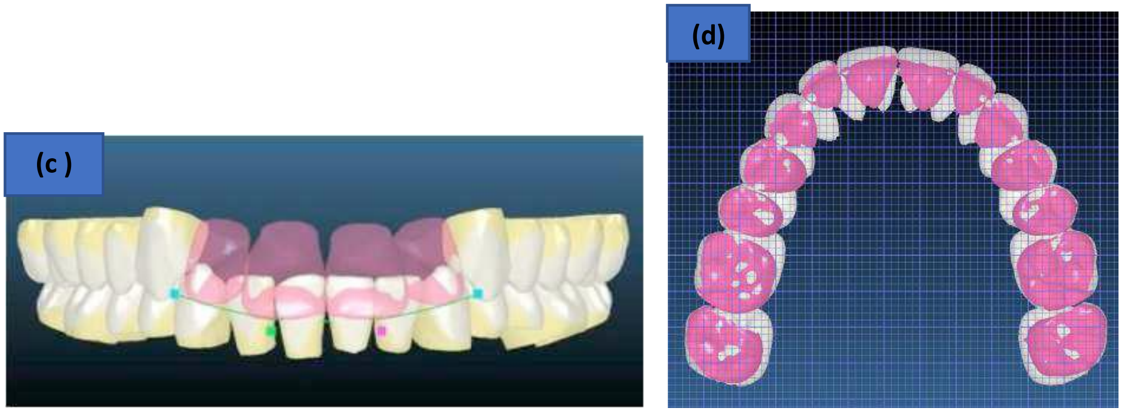
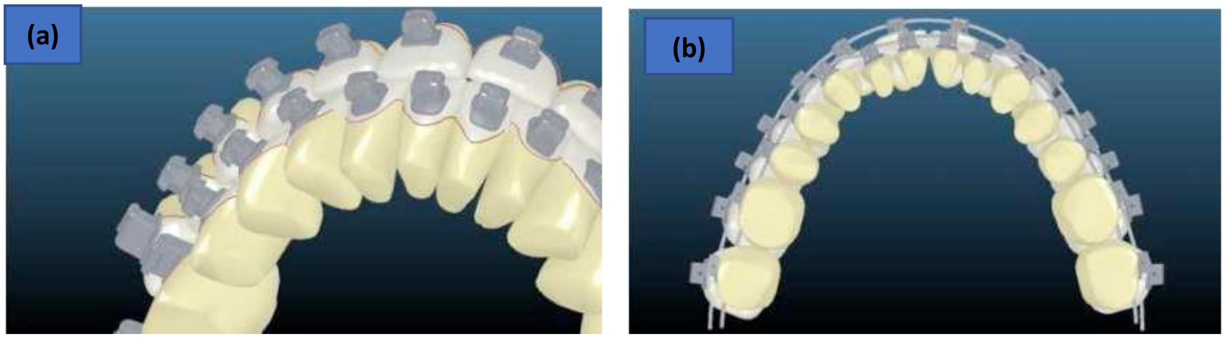


Figure 7. Insignia system (a) Insignia digital setup. The virtual compass tool (as shown on the maxillary right canine) can be used to change the 3D position of the tooth.(b) Tool enabling analysis of the mandibular bone so that the mandibular arch form is determined according to the patient-specific biologic limits. The modifications in the transverse dimensions can also be measured before and after the treatment simulation.(c) The smile arc can be modified by manipulating the maxillary anterior teeth.(d) Dental contacts in the final centric occlusion are shown as white areas **(Gracco *et al.*, 2013).**

The third phase in this system involves the construction of orthodontic appliances customized for the patient. This customization can be performed on three different components of the appliance; the bracket can be individualized, compensation bends can be added to the orthodontic archwires, and personalized jigs. The patient-specific appliances (brackets, archwire, and precision positioning devices) are not fabricated until the doctor has reviewed and accepted the virtual treatment planning **(Grauer *et al.*, 2012).** This digital information then is used to precisely cut each bracket by (CAD/CAM) technology, so that the slot for each bracket has the appropriate thickness, inclination, and torque needed for ideal positioning of that tooth, and archwires with an arch form established for that patient are supplied. The result is “the ultimate straight-wire appliance,” with wire bending reduced to a minimum if not totally avoided **(Proffit *et al.*, 2019)** (Figure 8).



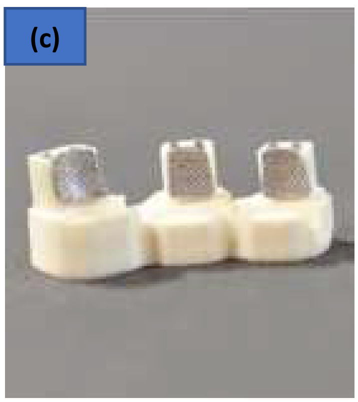


Figure 8. Bracket, Wires and transfer Jig of insignia system (a) Customized Damon Q brackets (Insignia SL) and torque-in-base molar tubes.(b) Occlusal view of the digital setup showing coordinated and customized maxillary and mandibular archwires with first-order compensation bends.(c) Insignia bracket transfer jigs for precise indirect bonding **(Gracco *et al.*, 2013)**.

Unlike many other systems, in which personalization entails the modification of the thickness of the composite used to adhere the bracket base to the tooth crown, in this system the brackets themselves are milled to the correct specifications **(Perri *et al.*, 2014).** Insignia self-ligating (SL) brackets are a customized version of Damon Q SL brackets (Ormco), which are individualized by varying the thickness and angulations of the metallic bases. When esthetic brackets are selected, no milling can be performed; therefore, customization is carried out by prescription selection, adjustments to the positioning jigs, and customized archwire design **(Gracco *et al.*, 2013).** An indirect bonding tray composed of bracket transfer jigs which precisely milled from sponge material that created to fit the occlusal surface of the tooth to transfer the virtual position of the bracket to the patient's mouth. Orthodontic treatment proceeds by arch wire progression **(Grauer *et al.*, 2012)**. The Insignia system also permits personalization of metallic archwires with first-order compensation bends; this can be done to all wires required to complete the treatment, whether made of CuNiTi, stainless steel or TMA **(Perri *et al.*, 2014)**.

Because the specifications for each bracket can be maintained in computer memory, it is possible to obtain a replacement bracket and bonding template within 2 to 3 weeks. Rebonding a loose bracket is done most efficiently by using the original bonding template, which should be kept with the patient's records for this possible reuse. In its absence, if alignment of the teeth has been completed, the archwire can be used to position the bracket. Even at that point, the custom brackets and archwires do not make the dental arches fit together. That relies on interarch relationships, which usually are provided by interarch elastics and are mostly under the control of the patient **(Proffit *et al.*, 2019).** A disadvantage of this system includes the potential for error in bracket positioning, either virtually or during transfer to the mouth. **(Grauer *et al.*, 2012).**

1.5 Clear Aligner Therapy (Invisalign)

With the recent increase in adults seeking orthodontic treatment, there has been a corresponding increase in demand for appliances that are both more aesthetic and more comfortable than conventional fixed appliances (figure 9) **(Tartaglia *et al.*, 2021).**

Figure 9. Conventional orthodontic treatment (a) and thermoformed clear aligner with its 3D printed mold (b)(**Tartaglia et al**., **2021**).

The formal introduction of clear aligners to the orthodontic armamentarium dates back to the 1998 FDA approval for Align Technology to employ Invisalign for orthodontic use **(Weir, 2017).** Kesling's appliance (the positioner) was a precursor to the Invisalign aligner. In 1945, Kesling predicted the future development when he stated that: "Major tooth movements could be accomplished with a series of positioners by changUUing the teeth on the setup slightly, as treatment progresses. It remains a possibility, however, and the technique for its practical application might be developed in the future" **(Ali and Miethke, 2012).**

Clear aligner is a natural extension of the use of tooth positioners and also spring aligners for tooth alignment that have been employed by orthodontists for many decades. Recently, with advances in transparent thermoplastic materials and computer technology (CAD-CAM, stereolithography and tooth-movement simulation software), this has resulted in clear aligner products being made increasingly available and effective for tooth alignment in a variety of malocclusions **(Weir, 2017)**. Invisalign aligners consist of a series of clear, removable, plastic appliances that the patient wears sequentially to achieve the final result. The Invisalign system uses a computer-based online software to plan the treatment ahead of time and the orthodontist can share the expected final results with the patients. Invisalign aligners were introduced to offer not only the advantage of better esthetics but also the convenience of removal during consumption of food and beverage, less pain, as well as better oral care **(Alajmi *et al*., 2020).**

1.5.1 The principles of the Invisalign® system

Pre-treatment records include photographs (extra-oral: frontal at rest/ smiling and profile; intra-oral: frontal, left/right lateral, maxillary/mandibular occlusal), and radiographs (figure 10). In addition, Align Technology also requires accurate maxillary and mandibular impressions made in a polyvinyl siloxane material along with a bite registration, both of them are scanned to permit the fabrication of a virtual model **(Ali and Miethke, 2012)**

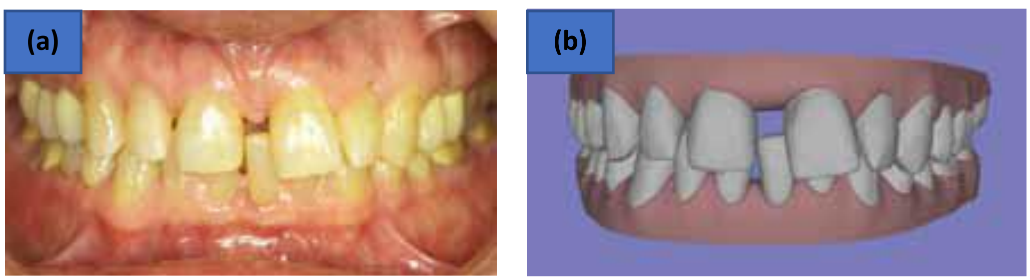


Figure 10. 3D-model by Invisalign (a) Intra-oral frontal view of a patient's dentition and (b) the corresponding 3D-model **(Ali and Miethke, 2012).**

A physical 3D model is needed for each individual aligner of the treatment set, and it is made using 3D printing, stereolithography or material jetting. Next, aligners are fabricated by molding the clear material over the 3D model of the patient's teeth (thermoforming or vacuum forming) and finally, trimmed. The process is long, labor intensive, and costly **(Weir, 2017).** Proprietary software (ToothShaper®) is applied to define the facial axes of the clinical crowns, colour-code all teeth, and separate them from each other, thus simulating work done on a plaster cast with a jig saw. All teeth receive a rudimentary root and are 'worked over', whereby any imperfections or artefacts are removed. At the same time, the gingival margin is demarcated, defining the extension of the anticipated aligner onto the alveolus **(Ali and Miethke, 2012).** After defining the boundary between the teeth and the soft tissue, virtual gingivae are draped over the alveolar processes, further enhancing the visual representation. Following this, the virtual model of the maxilla and mandible are orientated towards each other in centric occlusion by the application of another software tool **(Beers *et al*., 2003)**.

Basically, this program applies algorithms to maximize the tooth-to-tooth contacts. Using another software package, individual teeth are then aligned according to the orthodontist's prescription at an optimal rate, each treatment stage will move selected teeth by no more than 0.2 mm. This manipulation is controlled by a 'widget' which enables movements of a virtual tooth in all three planes of space **(Ali and Miethke, 2012).** The formulated therapy is then returned to the orthodontist in virtual form for evaluation by means of ClinCheck® software. Once approved, software will convert the virtual model of each treatment stage into a plastic model by using a process known as stereolithography **(Weir, 2017)**. Various thermoplastic materials, or combinations of materials, are being used for fabrication due to their excellent characteristics. These include; polyvinyl chloride, polyurethane, polyethylene terephthalate, and polyethylene terephthalate glycol **(Ercoli *et al.*, 2014).**

One of the negative results of the thermoplastic process that has been reported is that there are significant changes in the material properties in response to the heat generation used to form the material around the teeth **(Ryu *et al.*, 2018)**. The mechanical behavior of thermoplastic material used for the production of clear aligners plays a critical role in obtaining desired clinical results in difficult orthodontic movements, along with aspects such as aligner thickness regularity and geometry design **(Tamburrino *et al.*, 2020).** It has been observed that thermoformed clear aligners can have different thicknesses, ranging from 0.5 to 1.5 mm, which can certainly affect their properties and clinical performances, while inducing dental movement by pressure on the tooth's surface **(Tartaglia *et al.*, 2021)**.

While a higher thickness increases the delivered force by a bigger stiffness and the flexural modulus, the thermoforming process decreases these properties, depending on the thermoplastic material used and the thermoforming process performed. The homogeneity of thickness of the aligner plays an important role in the magnitude of exerted forces: discrepancies in the thickness influence the accuracy and the adaptation to the teeth **(Weir, 2017).**

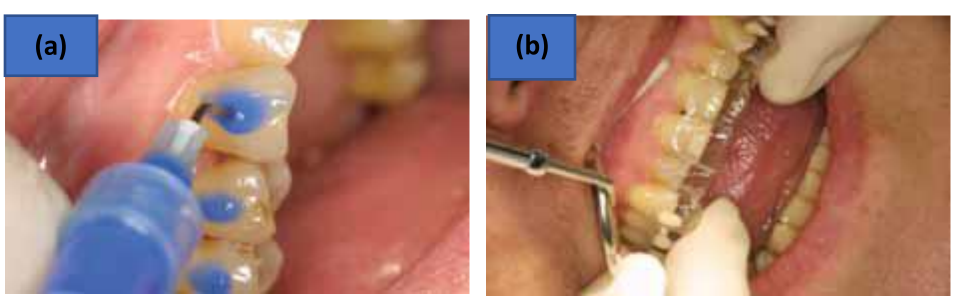
1.5.2 Development of Clear Aligners

3D printing could be used for direct printing of clear aligners by a single processing step using one or a combination of 3D-printing processes. Theoretically, various 3D printing processes may be used for direct printed clear aligners, such as fused filament fabrication (FFF), selective laser sintering (SLS) or melting(SLM), stereolithography (SLA), multi-jet photocured polymer process, HP MultiJet Fusion technology or continuous liquid interface production technology **(Tartaglia *et al.*, 2021).**

There are multiple clear resins used for 3D printing of appliances. In early 2018, EnvisionTEC announced the commercial release of E-Ortholign, an innovative material for the direct 3D printing of clear aligners. Objectively, the direct 3D printing of aligners offers several advantages over conventional fabrication **(Barone *et al.*, 2017):**

1. borders are digitally designed and identically reproduced for all sets of aligners;
2. edges are smooth and do not need trimming or polishing;
3. undercuts do not exist because they are digitally defined;
4. aligners are fabricated with higher precision as there are no errors introduced during printing of a 3D molding model and thermoforming stage of fabrication;
5. higher precision leads to better fitting and higher effectiveness;
6. aligner thickness is customizable, and this may reduce the need for attachments, which generally lower the transparency of clear aligners

Treatment with the Invisalign® system ultimately requires the use of 'attachments' akin to fixed appliance brackets. These small, custom-made composite shapes are bonded onto specific teeth in a manner similar to brackets. Attachments serve three main advantages : assistance with difficult movements, the augmentation of anchorage and support for auxiliary functions **(Weir, 2017)** (Figure 11).



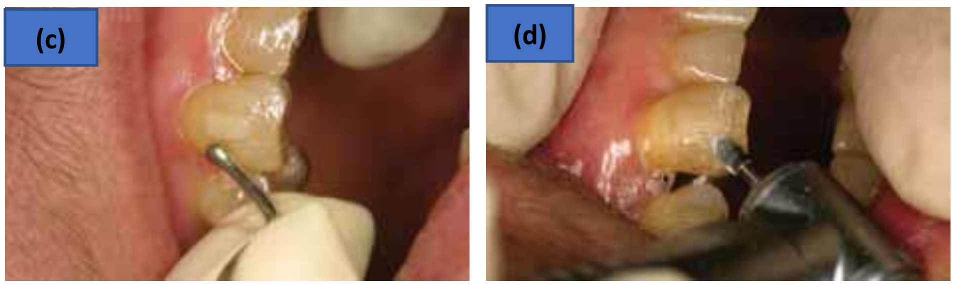
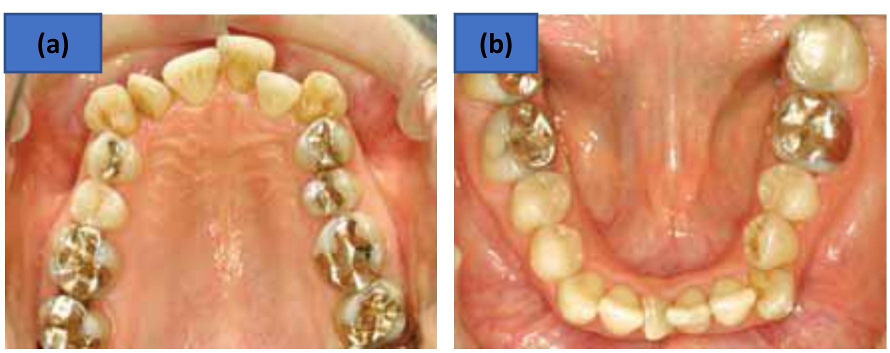


Figure 11. (a–d) Aligner attachment fabrication. **(a)** Application of etching gel on the respective teeth. **(b)** Insertion of a special very thin and flexible tray the concavities of which are filled with tooth-coloured composite. **(c)** Adaptation of the tray for defined shaping of the attachment. **(d)** Fine shaping of the composite body with a ball-end bur **(Ali and Miethke, 2012).**

Clear aligners provide advantages over treatment with traditional fixed appliances. These include fewer clinical emergencies and improved aesthetics, comfort, oral hygiene, periodontal health, and lack of soft tissue irritation (figure 12) **(Buschang *et al.*, 2014).** However, a significant limitation of the Invisalign system is the difficulty to alter the course of treatment once the set of aligners has been fabricated. If the final therapy outcome is unsatisfactory, the clinician may need to resort to the use of auxiliary devices (fixed attachments such as brackets), or request the fabrication of additional aligners **(Phan and Ling, 2007).**



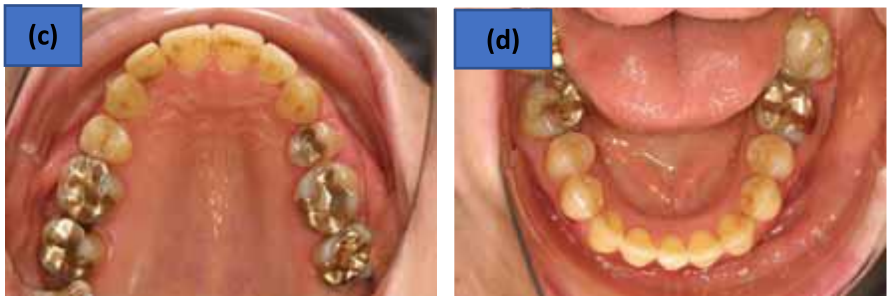


Figure.12 case treated by Invisalign, at the beginning **(a, b)** and at the end **(c, d)** of treatment after extraction of the maxillary first premolars and the mandibular right central incisor. The result was mainly accomplished with Invisalign® therapy, though some other invisible devices were temporarily also employed **(Ali and Miethke, 2012)**.

Chapter two

2.1 Discussion

Innovative systems capable of constructing orthodontic appliances customized for the patients have been introduced to the market in an attempt to provide more optimized orthodontic treatment outcomes as compared with conventional systems **(Perri *et al.*, 2014)**. Technologic advances in photography, digital scanning, and cone beam computed tomography (CBCT) have greatly improved the diagnostic and treatment planning procedures in orthodontics. Correspondingly, the application of computer-aided design and manufacturing technologies has allowed manufacturers to produce orthodontic appliances tailored to the specific tooth shape of the individual patient; i.e. customized orthodontic appliances **(Grauer *et al.*, 2012)**. This would provide the potential for decreased treatment and chair-side time, making orthodontic cases more predictable, accurate, and efficient. The need for time-consuming adjustments is greatly reduced, and appliance customization facilitates the achievement of the final desired occlusion from the first day of treatment. However, they still have disadvantages like any other system, such as the cost, technique errors that lead to extra time consumption because repetition of procedures may be required until getting satisfactory results **(Gracco *et al.*, 2013)**. In addition, the scientific evidence for the clinical effectiveness of most of these systems is insufficient so far.

The digital study models have disadvantages such as lack of tactile input, time required to learn how to utilize the system, extra time required for repetition when done inaccurately, scarcity of digital model supplier companies, questions surrounding the accuracy of digital models and additional costs **(Sharma *et al.*, 2015)**.

A clinical study was carried out on 180 patients by **(Penning *et al.*, 2017)** to evaluate the duration and outcome quality of orthodontic treatment with a customized fixed appliance system versus a non-customized system. The results showed that the customized orthodontic system was not associated with any significant reduction in treatment duration, and the treatment outcomes were comparable in both systems. Treatment duration and quality were affected by the orthodontist and the severity of malocclusion at the start of treatment rather than by the orthodontic system used.

On the other hand, when the Invisalign appliances are compared to the conventional fixed appliances regarding the range of malocclusion cases that can be treated, the Invisalign system can treat the mild and moderate cases such as crowding < 5 mm; spacing <5 mm; deep bites (Class II Division 2: correction by intrusion and protrusion of the incisors), constricted arches (correction avoiding unacceptable buccal tipping). However, it cannot treat the difficult cases such as crowding or spacing>5 mm; anteroposterior skeletal discrepancies >2mm; centric relation/centric occlusion discrepancies; severe rotations (> 20°); open bites (anterior and posterior); severe hypodontia/oligodontia and uprighting of severely tipped teeth (> 45°)**(Ali and Miethke, 2012)**.

Chapter three

3.1 Conclusion

1- Technological advances in orthodontics are not limited to customized appliances, but extend also to diagnostic and treatment planning tools. Intraoral scanners have the potential to replace impressions in the long run. Three-dimensional imaging (cone-beam CT) and three-dimensional cameras can enhance our diagnostic and treatment planning possibilities.

2- The customized orthodontic appliances can treat the mild and moderate cases of malocclusion. However, evidence needs to be justified by conducting further robust clinical trials and systematic reviews to verify and approve their clinical efficacy.

3- Unfortunately, minimal trials are so far available to harness the advances in digital orthodontics in addressing the severe cases of malocclusion.

3.2 Suggestions

1- More clinical trials and systematic reviews are required to confirm the clinical effectiveness about the digitally-driven orthodontic appliances.

2- The use of advanced technologies in improving the materials utilized in manufacturing clear aligners and other customized appliances must be encouraged to be successful in treating severe malocclusions.

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