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3D Printed Orthodontic Appliances

A Project Submitted to

The College of Dentistry, University of Baghdad, Department of Orthodontics in Partial Fulfillment for the Bachelor of Dental Surgery

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B.D.S. M.Sc.

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بسم الله الرحمن الرحيم

نَرفَعُ دَرَجَاتٍ مَن نَشَآءُ

وَفَوقَ كُلِّ ذِي عِلمٍ

عَلِيمٌ

CERTIFICATION OF THE SUPERVISOR

I certify that this project entitled "**3d Printed Orthodontic Appliances**" was prepared by the fifth-year student **Zainab Sadiq Jasim** under my supervision at the College of Dentistry/University of Baghdad in partial fulfilment of the graduation requirements for the Bachelor Degree in Dentistry.

Signature

Assist.prof. Layth Mohammad Kareem

B.D.S., M.Sc.

(Supervisor)

DEDICATION

To ALLAH my infinite love

My family my backbone, the real friends who surrounded me during this journey

My pure, strong, spiritual mind

Finally the super girl I was and I will always be

My MOM My Angel

ACKNOWLEDGMENT

First and lastly, all gratefulness, faithfulness and thankfulness to ALLAH for providing me with patience, perseverance and the ability to undertake and finally complete this study.

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LIST OF ABBREVIATION

CAD	Computer aided design
CAM	Computer aided manufacturing
3D	3 Dimensional
CBCT	Cone-beam computed tomography system
CT	Computed tomography
SLS	Selective laser sintering
PEEK	Polyether-ether-ketone
MARPE	Miniscrew-assisted rapid palatal expansion
RME	Rapid maxillary expansion
TMD	Temporomandibular disorder
NAM	Nasoalveolar molding
CAOT	Corticotomy-assisted orthodontic treatment
RP	Rapid prototyping
Fig.	Figure
STL and SLA	Stereolithography

INTRODUCTION

Since the beginnings of CAD/CAM in dentistry, the development of the technology has been inherently related to prosthodontics. The first application of CAD/CAM systems was the fabrication of dental restorations. Nowadays, further developments of CAD/CAM allowed for integration of the technology in other fields of dentistry, including maxillofacial surgery, dental implantology, and orthodontics **(Tomasz and Agata 2018).**

The main requirement to diversify the range of CAD/CAM applications is the progress in manufacturing technologies. Manufacturing can be held either with subtractive or additive methods. Subtractive fabrication is accomplished by removing material from a block by milling or cutting until a desired shape is created **(Bae *et al.*, 2017).**

On the other hand, additive manufacturing is referred to a process, in which an object is fabricated by adding a raw material layer-by-layer in a specific manner **(Andonovic and Vrtanoski, 2010; Bae *et al*., 2017).**

Other terms for this process used in literature are 3D printing (3DP) and rapid prototyping (RP) **(Beguma and Chhedat, 2014; Ligon *et al*., 2017).** One of the earliest applications of 3D printing in surgery, medical modelling, may be thought of as the production of an anatomical 'study model **(Kurenov *et al*., 2015)**. This has been made all the more accessible by another important technology that has become mainstream in dentistry in recent years CBCT has become widely available in dental practices **(Scarfe *et al*., 2006; Adibi *et al*., 2012)** .This allows anatomy, particularly complex, unusual, or unfamiliar anatomy, to be carefully reviewed and a surgical approach planned or practised before surgery **(Sinn *et al*., 2006; Van Assch *et al*., 2007).**

This has led to the development of new procedures and approaches to surgery and along with the production of drilling or cutting guides using 3D printed technology or conventional laboratory technology, can lead to expedited, less invasive, and more predictable surgery **(Sanna *et al*., 2007; Tardieu *et al*., 2007).**

With the use of intraoral optical scanners or laboratory scanners it is possible to develop a precise virtual model of the prepared tooth **(Akyalcin *et al*., 2013; Logozzo *et al*., 2014)** implant position **(Lin *et al*., 2015),** and the dental arch **(Akyalcin *et al*., 2013; Ender and Mehl, 2013).**

Three-dimensional cephalometry, which is done using a CBCT exam, allows for a more detailed evaluation of the craniofacial structure. With this method, the clinician can more easily detect and quantify craniofacial asymmetries, longitudinal growth and subtle occlusal changes **(Pinheiro *et al*., 2019; Juerchott *et al*., 2020).**

AIMS OF THE REVIEW

1- Investigate the efficacy and feasibility of using 3D printing technology in the fabrication of orthodontic appliances such as braces, aligners, and retainers
2- Assess the mechanical properties of different materials used in 3D printing in orthodontics.
3- Evaluate the clinical outcomes of patients treated with these appliances.
4- Inform the development of new and improved 3D printing techniques and materials for orthodontic applications, ultimately leading to better patient care and outcomes.

CHAPTER ONE
REVIEW OF LITERATURE

1.1 The digitization of orthodontic diagnosis and treatment planning

Intra oral scanners have now largely replaced impressions and study casts. The scans are considered as accurate if not more accurate than plaster models. The scanning process is more comfortable for patients especially with the reduced gag reflex. They are easily stored and also shared with any dental laboratory anywhere in the world through the internet without the need for the packing and sending impressions. This also eliminates two possible sources of error and material variability in the impression taking and handling and pouring and manipulation of plaster casts. The digital files can be sent to the lab, which can print them into a physical model or use them for direct digital appliance design and manufacture. Additionally the models are immediately available chairside for analysis and viewing. It is then faster and more accurate to undergo study model analysis and accurately calculate things like Bolton's tooth size discrepancy in a speedy and more precise manner when compared to plaster models **(Fleming *et al*., 2011)**. Furthermore the models can also be used in various orthodontic software platforms to allow the orthodontist to perform virtual treatment plans and explore various treatment plans within minutes as opposed to expensive and time consuming diagnostic setups and wax-ups. Performing digital setups not only allows the clinician to explore a number of treatment options in a simple manner it also facilitates better communication with other dental professional especially in cases that require combined orthodontic and restorative treatment **(Tarraf and Darendeliler 2018).**

With the use of digital software, an orthodontist can remove the existing brackets and appliances from the scanned dataset and design a new appliance. Thus, the orthodontist can deliver a new appliance immediately upon the removal of the old one. For example, the patient can be provided with a retainer immediately after debonding, eliminating the waiting period or perhaps a second visit. In case of breakage or loss of retainer, a replacement can be easily fabricated either by using printed models or from the digitally archived data **(Groth *et al*., 2018).**

1.2 Three-Dimensional Prognosis of Dental Arch Shape after Orthodontic Treatment

Orthodontic treatment plans should take into account the initial dental arch shape in order to achieve stable results. During the diagnosis stage, the arch shape should be evaluated (square, oval or conical), and the archwires used should be chosen according to their compatibility to each of these shapes. This technique relies solely on the operators' perception leaving it susceptible to mistakes. As such, 3D software has been developed to help better choose adequate archwires for each individual case. When compared to the conventional method, threedimensional systems have proven to be more accurate in dental arch shape assessment and final prognosis. Furthermore, these systems can provide the orthodontist quantitative difference values between the dental arch and existing archwires. However, this method is not ironclad, as studies suggest that the final prognosis accuracy is only of 60% due to factors, such as biological individuality, orthodontic biomechanics and supporting tissues **(Asquith and McIntyre, 2012).**

1.3 Advantages and Disadvantages of 3D Printing

Every technique, both traditional and innovative, is generally characterized by specific advantages and disadvantages which respectively promote and contrast the diffusion of the technique in question. Here is a summary of the pros and cons generally recognized for 3D printing **(Moharamzadeh *et al*., 2007; Hazeveld *et al*., 2014; Gupta *et al*., 2012; Neumeister *et al*., 2017; Osman *et al*., 2017; Camardella *et al*., 2017; Favero *et al*., 2017; Brown *et al*., 2018; Canzi *et al*., 2018; Cousley, 2020; Colombo *et al*., 2020; Sherman *et al*., 2020; Fayyaz *et al*., 2022)**

1.3.1 Advantages

The advantages of the digital workflow and 3D printing are:

- **Accuracy:** while traditional models might undergo technical errors and distortions, 3D-printed models might be more accurate as they involve less steps and no manual labor.

- **Comfort to the patient:** the scanning process might be more comfortable for the patients than the traditional impression technique.

- **Reduction of the times:** due to the absence of analogic impressions, clinicians can directly send digital STL files to technicians, resulting in a digital workflow much more rapid compared to the traditional one.

- Management of defects: during the elaboration of the digital model acquired, eventual scan defects can be solved guaranteeing a correct progression towards the printing of a reliable product.

- Reduction of environmental costs: considering that traditional dental impressions are avoided by substituting them with STL file, the digital workflow inevitably reduces the numbers of materials which would require to be specifically disposed of. Accordingly, environmental costs are significantly reduced.

1.3.2 Disadvantages

- Costs: the expense for the purchase of the 3D printing and hardware are significantly higher compared to the analogic workflow.

- Longer learning curve: specific training is required for clinicians to familiarize them- selves with the use of intraoral scanners to acquire a correct scanning guaranteeing a correct result of the entire process.

- The necessity of referral to specific technical laboratories: only laboratories with the available technologies required can be considered by clinicians working with a digital workflow.

- Health risk: specific procedures must be followed when handling uncured resins and cleaning solvents to avoid skin irritations caused by these materials. However, further aspects should be evaluated as regards the eventual toxicity of 3D-printed resins. In particular, monomer resins are recognized as toxic, despite their polymeric form generally are not.

1.4 Factors Affecting 3D-Printing Accuracy: (Sruthi, and Aravind, 2023)

1- **Build orientation:** Product accuracy and biocompatibility can all be affected by the build orientation.

2- **Layer thickness:** For each printing method, the ideal layer thickness may vary. It is faster to build with fewer slices (a thicker layer), but the precision is reduced as the layer thickness increases.

3- **Infill ratio:** This is a measure of the amount of solid material in the final printed object. The printer obtains the optimal infill ratio by changing the air gap between the produced lines.

4- **Postprocessing:** Postprocessing can significantly increase the performance of printed samples, but it comes at a cost and takes time. SLA advancement has been hampered by shrinkage and distortion of resin materials; however, the postcuring approach resolves this problem.

1.5 Removable Orthodontic Appliances Manufactured by 3D printing

First trials to manufacture removable acrylic orthodontic appliances using computer-aided design and 3D printing have been made and presented by **(Sassani *et al*., 2014).** The authors reported the application of half-automated technique to manufacture acrylic base plates of removable appliances. A machine dedicated for this particular purpose has been used to add and polymerize layers of acrylic, which were added according to the computer design of the appliance. The screws and wires however needed to be placed manually onto the working model, their incorporation in the virtual design and manufacturing process has been reported not to be possible at that time **(Sassani *et al*., 1995; Al Mortadi *et al*., 2012)** described a procedure of Adresen activator and sleep apnea appliance fabrication using computer-aided design and additive manufacturing technology. The first step in the procedure was digitalization of plaster models of patient's dentition using a laser scanner. Construction bite and virtual appliance design was made using CAD software (FreeForm Modeling Plus, version 11; Geo Magics SensAble Group, Wilmington, Mass) in conjunction with special phantom (haptic) arm (Geo Magics SensAble Group). The acrylic baseplate of the appliance has been designed. The design involved modeling of a palatal plate, bite blocks covering occlusal surfaces of mandibular, and maxillary teeth to form a monoblock and anterior capping covering lower incisors. The labial bow was bent manually in a conventional way, with 0.9 mm stainless steel wire.

Al Mortadi *et al*., 2015 presented 3D printed Hawley retainer manufacturing using intraoral scans obtained with TRIOS (3Shape, Copenhagen, Denmark), eliminating the need of conventional impression taking and pouring plaster models. During the stage of creating virtual appliance, the shape, thickness and range of acrylic base plate, fitted labial bow, and Adams clasps was designed. Wire elements were bent using cobalt-chromium alloy with 3D printing technology. The base plate of Hawley retainer was fabricated form ClearVue resin material (3D Systems), implementing stereolithography. In clinical assessment of the retainer, the quality of the appliance was satisfactory. A disadvantage of the described procedure is the necessity to use complex software and haptic phantom arm, which significantly increases cost of the procedure. On the other hand, strictly controlled manufacturing process is reliable and repeatable, allowing to create appliances with planned thickness, range, and shape (fig. 1-1).

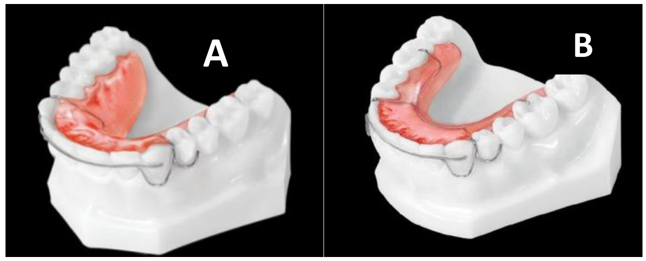


Figure (1-1): (A) Hawley Retainer with flat bow for upper arch (B) lower arch **(Al Mortadi *et al*., 2015)**

1.6 Customized Orthodontic Brackets

A customized appliance system uses digital models of the patient's arches to simulate the optimal position of each dental element and the ideal final occlusion (fig. 1-2) **(Saxe *et al*., 2010; Sachdeva, 2001; Mah and Sachdeva, 2001; Vassura *et al*., 2010; Scholz and Sarver, 2009).** Once the desired virtual result is achieved, the personalized archwires, brackets, and indirect-bonding transfer jigs are produced. using Insignia's software to refine the torque, tip, in/out, intrusion, and extrusion of each tooth, archform, within the patient biological limits set by the osseous structure, smile arc and dental contacts in the final centric occlusion.

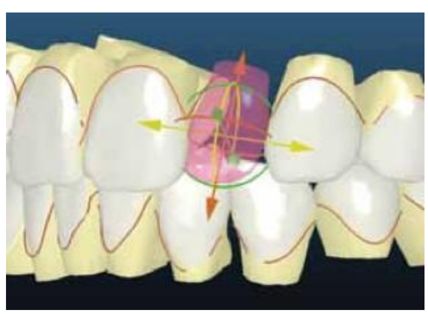


Figure (1-2): Insignia digital setup; virtual compass tool shown on lateral incisor changes tooth position in three dimensions **(Atonio and Stephen, 2011).**

Unlike computerized methods that simply modify the thickness of the bracket adhesive, the Insignia system reverse-engineers the brackets themselves to the correct specifications in one of two ways, depending on the type of brackets selected by the orthodontist. Insignia metal twin brackets are individualized by precision-cutting the slots in the milled-in faces. One important feature recently added to the Insignia system is called “Overcorrection”. This program tracks the three-dimensional movements of the center of resistance of the roots and the center of the bracket slot for each tooth, then calculatesthe tooth’s direction of rotation with respect to 3rd-order constraints. Most clinicians use archwires that are undersized relative to the slot, resulting in about 10° of play. Another unique feature of the Insignia system is its customization of archform, based on skeletal mapping of the mandibular bone’s cortical limits at the level of the center of resistance of the teeth (fig. 1-3) **(Atonio, G. and Stephen, T. 2011).**

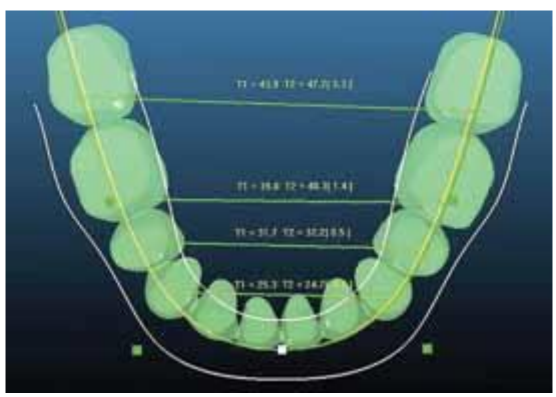


Figure (1-3): Analysis of mandibular bone **(Atonio and Stephen, 2011).**

For children CAD software has given practitioners the ability to individualize their orthodontic bracket prescription by direct-printed brackets. This is a promising advantage that could result in a more accurate and faster orthodontic treatment. The software enables the orthodontist to perform a setup while the software positions the virtual brackets on the teeth which are later printed in permanent crown resin or zirconia. Printed zirconia has high hardness, it is aesthetic, but has low fracture toughness While the metals’ fracture toughness is proven, there are no studies that have looked at the fracture toughness of printed zirconia , This is the reason why we can only use zirconia for passive appliances such as lingual arches and nance appliances, but we cannot use it for rapid maxillary expanders and distalizing appliances (fig. 1-4) **(Ioannis *et al*,).**

Figure (1-4): Customized brackets for children **(Ioannis *et al*, 2022)**

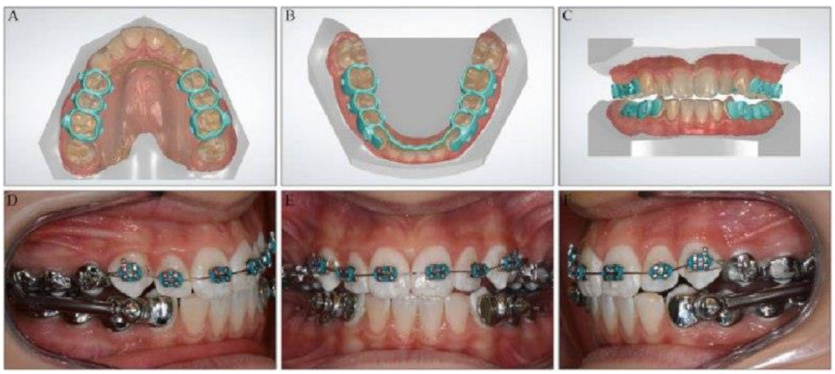
1.6.1 Hyrax – Halterman

This appliance is a combination of a hyrax and a Halterman to perform simultaneous maxillary expansion and distalization of the ectopic molars **(Teeters, 2017)**. Buccal cantilever arms extended distally from the saddle bands on the deciduous second molars. Buttons were bonded on the occlusal surfaces of the first molars and elastic chains were connected from the buttons to the arms **(Simon *et al*., 2021)**

Figure (1-5): Hyrax-hayrake-blue-grass combination. (A) CAD-CAM design. (B) Printed appliance with jackscrew welded afterwards. (C) Appliance inserted with movable blue-grass bead **(Simon *et al*., 2021)**

1.6.2 Herbst with brackets

This appliance has buccal brackets, rather than conventional tubes, added to the Herbst framework (fig. 1-6). The bracket slot better controls the torque and the wings aid in placement of an elastic chain or a steel-ligature. If a precise slot-wire engagement is required, for example, in the lower arch where incisor torque control is crucial, then the bracket slot should be printed slightly undersized **(Simon *et al*., 2021).**



Figure(1-6): Herbst with brackets bonded Ultra Band-Lok.(A) Maxillary CAD-CAM. (B) Mandibular CAD-CAM.(C) Frontal CAD-CAM. (D) Right-side view with appliance inserted. (E) Frontal view.(F) Left-side view **(Simon *et al*., 2021).**

1.6.3 Space Maintainer Appliances

1.6.3.1 Lingual Arch Design

A lingual arch can easily be designed. It consists of two bands and an arch which is also designed by selecting the area on the anterior teeth where the arch will pass. Usually, the thickness of the arch is around 1 mm, and the height is 0.7 mm. A disadvantage of a customized lingual arch is that no loops can be positioned near the molar in case of a needed adjustment (fig. 1-7) **(Wolf, 2015).**

Figure (1-7): A lingual arch designed in Meshmixer and printed using CoCr alloy in SLS printer **(Wolf, 2015).**

1.6.3.2 Unerupted Molar Tooth Guiding Appliance

In the case of a premature second deciduous molar loss, the first permanent molar most often tips anteriorly trying to find the distal part of the second deciduous molar in order to erupt. This creates problems for the molar itself, since after erupting it has to be orthodontically straightened, but also due to the loss of space for the eruption of the second premolar. For this reason, it is essential to design an appliance that will guide the molar to erupt in its position or prevent it from erupting mesially (fig. 1-8) **(Ioannis *et al.*, 2022).**

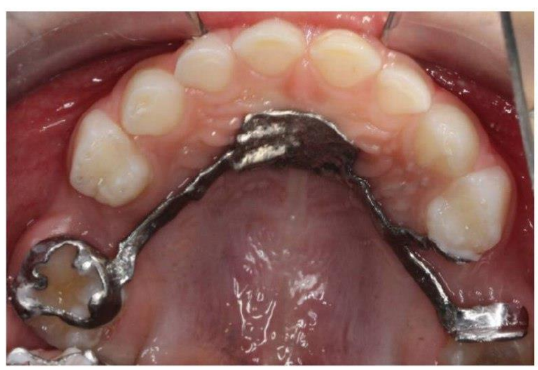


Figure (1-8): An unerupted molar eruption Nance hybrid guiding appliance **(Ioannis *et al.*, 2022).**

1.7 Removable Orthodontic Retainers

Computer-aided design and 3D printing open new possibilities in orthodontics to manufacture customized removable retainers. The procedure has been presented and described by **Nasef *et al.*, 2014.** The process integrates the application of new technologies, including cone beam computed tomography (CBCT), CAD and 3D printing. The first step in the procedure is scanning patient's dentition using CBCT and image conversion into a STL file to create a 3D model of patient's dentition. Following importing the file into dedicated software (Zbrush 4R4, Pixologic, Los Angeles, California), the retainer is designed virtually. The virtual project representing the retainer is (upon acceptance) manufactured by printing**.** However, according to the authors, the described method may be successfully used with other 3D printing technologies and materials **(Nasef *et al.*, 2014).**

Figure (1-9): 3D printed Hawley retainer **(Nasef *et al.*, 2014).**

1.8 Bonded Orthodontic Retainers

In recent years, bonded retainers can be manufactured using CAD– CAM systems. The studies in this area are limited as this is a very new technology. The techniques and types of wires used for manufacturing bonded retainers using CAD–CAM technology vary for each firm. In one of the techniques used, the retainers are produced by bending of prefabricated wires by the handle of a machine. The SureSmile retainer (OraMetrix, Richardson,TX, USA) that is produced by this technique uses copper–nickel–titanium wires **(Sachdeva, 2001)**.

Another technique is producing bonded retainers by carving out of a block of wire. The Memotain retainer (CA-Digital, Mettmann, Germany) that is produced by this technique is manufactured from nickel–titanium wires of 0.014×0.014 inch thickness **(Kravitz et al., 2017).**

1.8.1 Nickel - Titanium Lingual retainers

A new CAD/CAM fabricated lingual retainer wire made of custom cut nickel-titanium—as an alternative to multistranded lingual retainers. Memotain (fig 1-10) is a CAD/CAM fabricated lingual retainer made of 0.014x0.014-in rectangular nickel-titanium. The wire is very versatile and custom move exactly adapt to the patient's lingual tooth anatomy. It was fancied in 2012 by associate degree dental practitioner, Pascal Schumacher.

The name Memotain may be a portmanteau from the mix of "memory" and "retainer" due to the individuality of use nickel titanium for the lingual wire **(Angaj *et al.*, 2019).**

Figure (1-10): Memotain on the lingual surface of the upper arch **(Angaj *et al.*, 2019).**

1.8.1.1 Benefits of Memotain: (Angaj et al., 2019)

1. No need for wire measuring or bending.

2. Individually optimized placement, greater accuracy of fit.

3. Tighter interproximal adaptation, less tongue irritation.

4. Better durability, and resistance to microbial colonization.

1.8.2 PEEK Fixed Retainers

Different materials sometimes are need to treat patients with metal allergies or other issues requiring metal-free devices **(Littlewood *et al*., 2017; Beretta and Cirulli, 2017).** Among the polymers that have recently been introduced in dentistry and orthodontics, PEEK has been proposed as a viable alternative to metal. PEEK is a semicrystalline linear polycyclic aromatic polymer that was developed in 1978 and later commercialized for industrial purposes **(Ma and Tang, 2014).** By the late 1990s, PEEK had become prominent as a high-performance thermoplastic used in orthopedic surgery **(Ma and Tang, 2014).** Dental devices made with PEEK can be either milled or 3D printed, offering versatility in production (fig. 1-11) **(Mangano *et al*., 2019).**

Figure (1-11): Bonded lower PEEK retainer **(Beretta *et al*., 2021).**

1.9 3D- Printed Retainers Compared with Thermoform Retainers

The traditional vacuum-formed retainers showed the least amount of deviation from the original reference models. The 3D-printed retainers showed the greatest deviation at the reference points located on the smooth surfaces of the teeth but showed close adaptation at the incisal edges and cusp tips. The 3D-printed retainers seem to be similar to the traditional vacuum-formed retainers in fit. Further clinical trials are needed to assess their clinical performance (**David *et al*., 2019).**

1.10 The Use of 3D- printing In Distraction Oseteogensis

The distraction osteogenesis in craniomaxillofacial region is used to lengthen and/or reposition the mandible, maxilla, and/or craniofacial structure for craniofacial or dentofacial deformity. It is mainly indicated for the treatment of overwhelming skeletal and/or dental discrepancy that is difficult to treat by general surgical procedure **(Ko, Chen and Lo, 2017).**

The digital diagnosis, evaluation, and simulation of craniomaxillofacial disorders using three-dimensional (3D) computed tomography (CT) and various digital technologies are coming into wide use. Designing a composite craniomaxillary-dental model by replacing the dental part of a CT model with a scanned dental model allows accurate dentofacial analysis and surgical simulation with delicate interdental occlusion More over, the designed surgical device can be accurately produced following the simulation and computer-aided design (CAD) using 3D printing with stereolithography technique **(Kang *et al*., 2015).**

1.11 MARPE

Rapid maxillary expansion (RME) devices have been routinely used in the correction of transverse discrepancies such as unilateral, bilateral crossbite in young individuals **(Lagravère *et al*., 2010).** However, managing problems in the transverse dimension in adults has always been a challenge. To overcome this, miniscrew-assisted rapid palatal expansion (MARPE) device was introduced **(MacGinnis *et al*., 2014).** The regular MARPE and the MSE has been effective in bringing about skeletal expansion in adults, yet they have serious limitation in cases of narrow and high arched palates. The standard expansion screw sometimes does not fit into the palatal depth and therefore due to faulty screw insertion, the anchorage becomes seriously compromised. Customization of MARPE would bring about—almost in every case—better fit and adaptation, choice of options in design, two screws or fours screw options, and better rigidity (Cr-Co alloy) to the system which would invariably bring better and more predictable skeletal expansion. The advantages of the customized design clearly contemplate that the future lies in this form of appliances (fig. 1-12) **(Graf *et al*., 2016; Aragón et al., 2016).**

Figure(1-12): 3D Printed MARPE Assembly Laser Welded on the Hyrax **(Digant *et al*., 2020).**

1.12 Occlusal Splints

Occlusal splints are contemporarily used for treatment of patients presenting with temporomandibular disorders (TMD). The conventional process of splints fabrication in dental laboratory requires taking alginate impressions of patients dentition, wax bite registration, and mounting casts in articulator. Lauren and McIntyre were the first authors to publish an article, which describes digital workflow in occlusal splints manufacturing **(Lauren and McIntyre, 2008).** The suggested digital protocol applied subtractive technology of splint fabrication, which were machined down from acrylic material block**. Salmi *et al*., 2013** introduced 3D printing into the process of splint manufacturing (fig. 1-13). Occlusal splints were made by the authors using stereolithography machine SLA 350 (3D Systems, USA). 3D printed splint has been evaluated clinically after 1, 3, and 6 months of patient's use. The adaptation process to splint therapy has been positive and muscle tension has been relieved. No signs of tooth or splint wear has been detected after 6 months of clinical use 56. Moreover, the splint has been thoroughly tested following scanning and the scan was superimposed onto splint virtual design with special software. Inaccuracies in splint dimensions and surface deviations of 1 mm were reported at the edges and sharp margins of the splint; however, maximal deviations in other parts of the appliance did not exceed 0.3 mm **(Salmi *et al*., 2013).** These findings indicate that 3D printing has potential to become routinely used in occlusal splints manufac-turing. The printing process is highly reproducible and faster than conventional technique, thus decreases significantly the dental laboratory workload. According to the authors, improved 3D printed splint accuracy may reduce time required to trim the splint **(Antoszewska *et al*., 2009; Salmi *et al*., 2013).**

Figure (1-13): 3D printed occlusal splint **(Salmi *et al*., 2013).**

1.13 Three-Dimensional Printing in Cleft Care

1.13.1 Nasoalveolar Molding

Nasoalveolar molding involves constructing a molding plate from a cast of the patient's maxilla, which is attached to a nasal stent. This is modified on a weekly or biweekly basis to "mold" the nasoalveolar defect nonsurgically in order to improve symmetry, project the nasal tip, elongate the columella, align the alveolar ridges, and decrease the gap between the cleft lipsegments **(Grayson *et al*., 1999; Grayson & Garfinkle, 2014)**.This complex, manual process of manipulating the patient molds requires high expertise, is time-consuming, and efficacyand efficiency of the treatment are dependent upon the practitioners' skills **(Schiebl *et al*., 2019; Zheng *et al*., 2019)**.

Three dimensional printing expedites the NAM process by reducing time, effort, and cost for both provider and patient **(Yu et al., 2011; Schiebl *et al*., 2019; Zheng *et al*., 2019).** Using scans of infant maxillary impressions, molds can be modified virtually and printed via additive manufacturing, creating multiple NAM devices at once after a single mold **(Yu *et al*., 2011; Gong & Yu, 2012).** Algorithms for semiautomated generation of NAM devices allow providers to generate multiple templates with a single initial mold. After virtual manipulation, this can be used to reliably 3D print NAM devices as measured by deviation between printed plate models and patient upper jaw models, effectively eliminating the need for manual manipulation by the clinician on a weekly basis **(Schiebl *et al*., 2019)**. The clinical implications of streamlining NAM therapy with virtual planning and 3D printing include reducing frequency of appointments, decreasing the number of impressions/casts required, and minimizing the time-intensive manual adjustment of plates by the provider **(Yu *et al*., 2011; Schiebl *et al*., 2019; Zheng *et al*., 2019).**

1.13.2 Surgical Planning/Volumetric Analysis

In cleft lip and palate care, volumetric analysis of nasoalveolar cleft defects has largely been used for surgical planning. For these defects, iliac crest bone grafting stabilizes the maxilla by restoring continuity and preparing the maxilla for future orthodontic treatment **(Jia *et al*., 2006; Du *et al*., 2017).** Commonly, surgeons use intraoperative estimates from prior experience for autologous graft volumes rather than objective criteria **(Chen *et al*., 2020).**

Three dimensional printing and virtual 3D modeling allow for nearly equally accurate and precise measurements of the defect volumes in patients with unilateral and bilateral cleft lip and palate **(Du *et al*., 2017; Kasaven *et al*., 2017; Chou *et al*., 2019; Chen *et al*., 2020).** Assessing the accurate volume of the alveolar defect may be helpful in surgical planning as it determines selection of donor site and contributes to the treatment outcome

(Chou *et al*., 2019). In addition, volumetric analysis can guide the size of the iliac bone harvest, minimizing donor site morbidity and potential for iatrogenic complications such as pain, hematoma, pelvic instability, nerve injury, or poor cosmesis **(Chou *et al*., 2019; Chen *et al*., 2020).** Conversely, inadequate harvest risks failure in restoring the dental arch **(Du *et al*., 2017).**

1.13.3 Surgical Simulation and Training

Developing the anatomic understanding and honing the numerous surgical techniques for cleft lip and palate repair presents its own set of challenges. Not only are the surgeries less common than other reconstructive surgeries, they are complex and require understanding of 3D anatomic malformations, evaluation of defects with various widths and sizes, and a feel for the fragility of the infantile tissues **(Cote *et al*., 2018).** A trainee must accomplish all of this with limited access to and visualization of the surgical site **(Cote *et al*., 2018)**. In 1 study, operative times increased by 104% when trainees were involved in cleft lip and palate repair surgeries **(Sasor *et al*., 2013).** This increases the operative risks and monetary costs to the patient **(Sasor *et al*., 2013).** 3- Dimensional printing offers a solution by providing tactile models for surgical simulation and training (fig. 1-14).

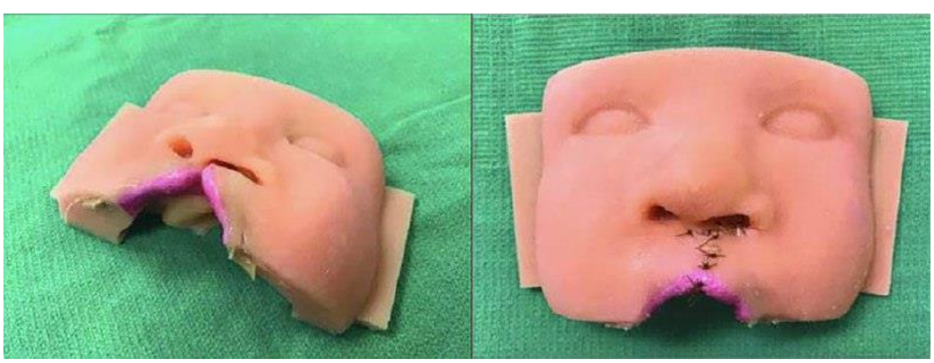


Figure (1-14): 3D printed cleft lip simulator **(Reighard *et al*., 2019).**

1.14 Surgical Guide Technique for Miniscrew Placement

The use of miniscrews in orthodontics has notably increased in recent years. Minis-crews allow for the simplification of several treatment plans by producing skeletal anchor-age. Since these are easy to place and remove and require no cooperation from the patient, there has been an increased use of these devices in orthodontic practices. However, the stability heavily relies on bone thickness both on a vestibular and palatal level. Miniscrews are also difficult to correctly place, and there is a risk of dental damage, sinus or nasal perforation, chronical sinus inflammation and even anchorage loss **(Möhlhenrich *et al*., 2020).** Bone thickness varies from individual to individual so orthodontists must always assess each case before placing any miniscrew. The development of three-dimensional imaging exams has improved diagnosis and treatment plans by eliminating issues related to twodimensional imaging **(Cassetta and Giansanti, 2016).**

Through the superimposition of CBCT and digital models (intraoral scan), it is possible to evaluate the best placement area for miniscrews. After determining the preferred placement site, a surgical guide can be manufactured using a 3D printer (fig. 1-15). These guides will provide a precise and controlled placement while simultaneously minimizing risks commonly associated with this procedure**(Cassetta and Giansanti, 2016; Maino *et al*., 2016; Möhlhenrich *et al.*, 2020).**

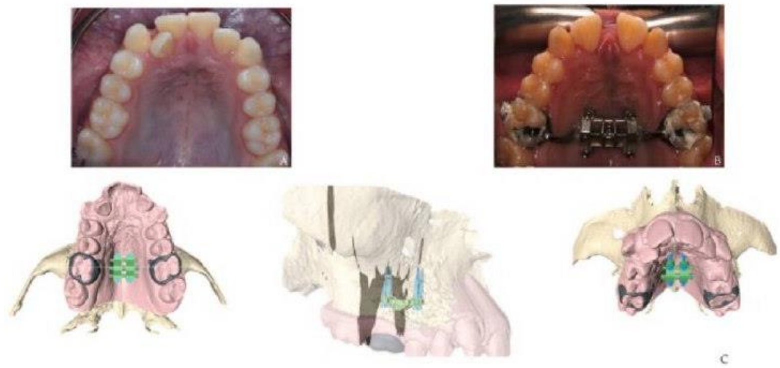


Figure (1-15): Planning the placement of micro-implants in the maxillary expander:

(A) Initial occlusal photo. (B) Placement of the microimplant assisted rapid palatal expander. (C) Microimplant placement planning through the superimposition of CBCT and digital models **(Inês *et al*., 2022).**

1.15 Corticotomy Technique Using CAD/CAM 3D Printed Surgical Guides

A corticotomy is defined as a premeditated defect that is inflicted on the cortical bone, decreasing its resistance and drastically reducing treatment time. This technique is considered to be the only effective and low risk intervention that accelerates tooth movement. This approach is commonly referred to as a corticotomy-assisted orthodontic treatment (CAOT), and it consists of administering small cuts along the area of alveolar bone where the movement are desired to take place. Although this method does present many advantages, corticotomies are, many times, still responsible for significant post-surgical discomfort. In order to bypass this possible discomfort, a minimally invasive procedure has been developed. This intervention relies on 3D-printed CAD-CAM surgical guides that have piezo surgical micro incision lines. In order to manufacture these guides, first, a preliminary impression of both arches extending to the vestibule is taken, and an individual tray is manufactured in order to make a second impression that will be subsequently digitized with a 3D scanner. The model images and matching acrylic surgical template are stored as an STL file **(Cassetta and Giansanti, 2016).**

1.16 Assessment of Tooth Movement in a Three Dimensional Plane

The magnitude of orthodontic movement is reliant on several factors, such as the amount, duration and direction of the applied force; the force-momentum ratio; and the supporting periodontal tissues. Dental movement assessment is commonly achieved by resorting to a panoramic radiograph, which should be done before, during and after treatment. However, this exam is not accurate for root position assessment since it suffers distortions. CAT scans and CBCTs are far more accurate and precise for this purpose. However, since orthodontic treatment requires frequent root movement monitoring, resorting to a CBCT or a CAT scan every single time would expose the patient to increased levels of radiation (fig. 1-16) **(Lee *et al*., 2015).**

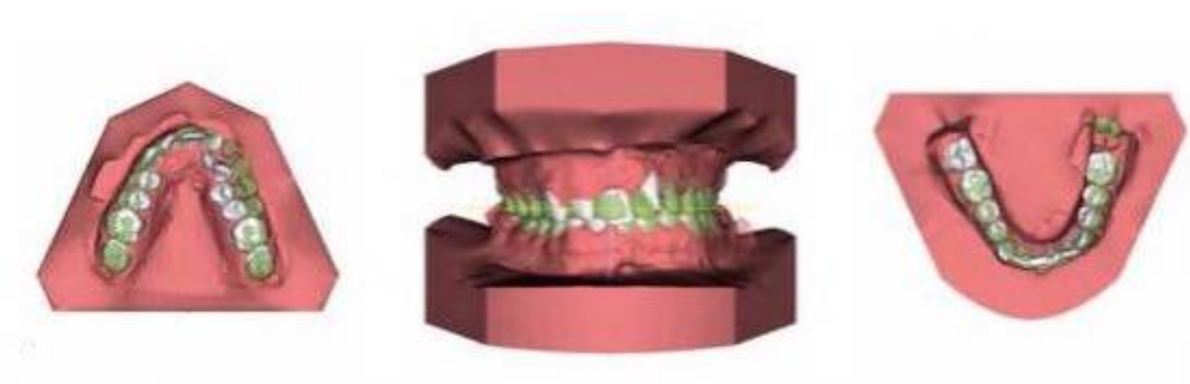


Figure (1-16): Three-dimensional tooth movement evaluation **(Inês et al., 2022).**

1.17 Photorealistic Visualization of Rendered CT Images

The CBCT exam is necessary to accurately visualize soft tissues. However, these do not have a photorealistic appearance, which is imperative in cleft lip and palate diagnosis, scarring assessment and orthognathic surgery prognosis. As an alternative, the photorealistic virtual face is a method that involves the overlaying and fusion of a CBCT soft tissue image with 3D stereophotographic images of the patient (fig. 1-17) **(Plooij *et al*., 2011; Lin *et al*., 2015).** Stereophotogrammetry has evolved in recent years, and these methods now require two images one of each side of the patients' face to create a 3D model that can be observed and measured regardless of perspective **(Monteiro, 2022).** Computer technologies have improved these techniques making the capture and building systems faster, simpler and more precise **(Manosudprasit *et al*., 2017).**

Figure (1-17): Combination of stereophotogrammetry images with CBCT images to create 3D virtual models of the patient: (A,B) untextured soft tissue surface of the CBCT scan. (C) Fusion of a CBCT soft tissue image with 3D stereophotographic images **(Inês *et al*., 2022).**

1.18 Orthognathic Surgery 3D Planning Surgical Splint Manufacturing

Conventional orthognathic surgery planning relies on computer assisted two- dimensional surgical simulation systems, which integrate photographs and cephalograms as a guide **(Aristizábal *et al*., 2018; Donaldson *et al*., 2021).** Along with these systems, a facial arch is used in order to adequately register the patients' bite in a semi-adjustable articulator. This process allows for a simulation of surgical movements using the patients' cast models, which is necessary for surgical splint manufacturing **(Vale *et al*.,**

2016). Although this method is well established and widely used, it has a few setbacks, since the use of a conventional articulator and planning of three-dimensional procedures using two-dimensional imaging can create imprecisions **(Donaldson *et al*., 2021)**. Three-dimensional simulation systems with CBCT have arisen as a solution to some of the issues previously mentioned with two-dimensional planning **(Vale *et al*., 2016; Aristizábal *et al*., 2018; Donaldson *et al*., 2021).** These techniques require a CBCT, and, to perform this exam, the patient must have the head and muscles in a natural position with a relaxed expression while biting in centric relation **(Elnagar *et al*., 2020; Donaldson *et al*., 2021).** Skin texture and structures must be refined and improved in order to accurately overlay with the CBCT reconstruction, and this can be done by mapping 2D photographs, using 3D photographs or a 3D surface scan with CBCT reconstruction data. When it comes to intraoral structures and dental artefacts, this refinement can be achieved through the digitization of the plaster casts, direct intraoral 3D scanning and scanning of the dental impression with a CBCT or a surface laser scanner **(Vale *et al*., 2016; Aristizábal *et al*., 2018; Donaldson *et al*., 2021).** The scan should be done immediately after the CBCT in order to avoid any issues during the rendering process. The bite register must be obtained with precision, and, in cases of functional deviations or double bite with multiple interferences, several bite records should be done in order to avoid imprecisions **(Elnagar *et al*., 2020).** Using this approach, the segments are repositioned by translation movements in relation to the three spatial planes (x, y and z), and adjustments are made by rotation around these axis representing "roll, pitch and yaw" **(Aristizábal *et al*., 2018; Donaldson *et al*., 2021).** Furthermore, it is possible to identify relevant surrounding structures that can interfere in the osteotomy process, such as the maxillary sinus, dental roots and inferior alveolar nerve **(Donaldson *et al*., 2021).** After the 3D surgical planning, the surgical splints a can be manufactured using CAD/CAM techniques. Guide models to predict surgical cuts and the location of screws and surgical plaques can be planned in the 3D program (fig. 1-18) **(Elnagar *et al*., 2020; Donaldson *et al*., 2021).**

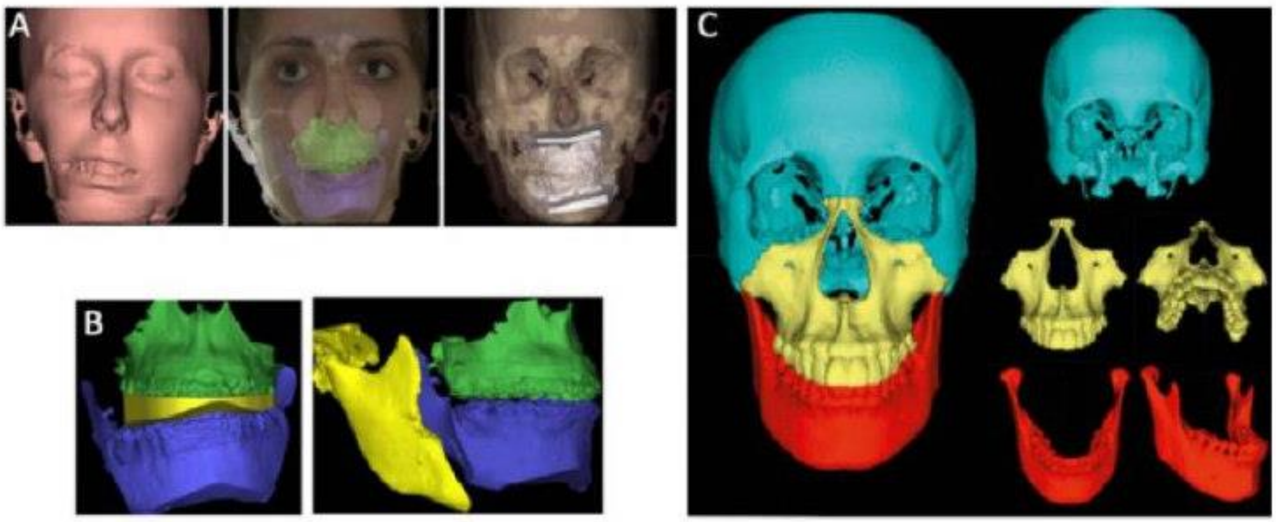


Figure (1-18): 3D Orthognathic Surgery planning: (A) Preoperative virtual simulation. (B) Predicted results on hard tissues. (C) Postoperative virtual simulation of the predicted results on hard tissues **(Inês *et al*., 2022).**

1.19 Clear Aligner Manufacturing

Clear aligners (fig. 1-19) are based on systems that are highly reliant on 3D technologies, such as CBCT and especially intraoral scanners. With the use of the intraoral scanner, the orthodontist can create 3D models of the patients' mouth and set up the orthodontic movements desired with the use of a specific automatic adjustment software for the soft tissues. In a singular clear aligner case, several trays are needed in order to achieve the projected result. The aligner sequence is responsible for a gradual orthodontic movement and as such, for each movement, there is a different model and subsequently a different tray. After diagnosis, the orthodontist must define the intended outcome on the software prior to treatment. During this stage, the clinician must also divide the desired dental movements, which will result in the number of aligners necessary for the projected results. After all the projections, each 3D model is converted into an STL file so that they can be 3D printed. These models will then be used to make the aligners with thermoformed plastic **(Ritto *et al*., 2011).**

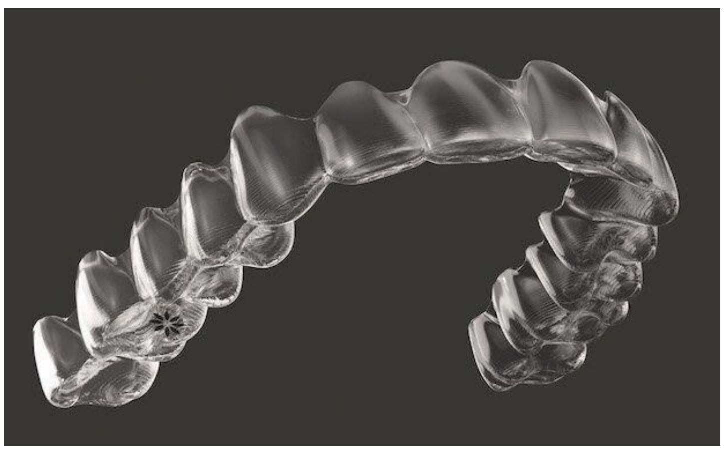


Figure (1-19): 3D printed aligner **(Ritto *et al*., 2011).**

CHAPTER TWO

DISCUSSION

The results of this review show that a wide range of 3D-printed devices has been clinically trialed, but few articles have rigorously assessed the efficacy or effectiveness of clinical 3D-printed devices. (**Sruthi and Aravind, 2023).**

Analysis revealed that the use of 3D printing, orthodontic appliances can be made easily and more accurately. Most commonly 3D-manufactured metal appliances are hyrax- style rapid palatal expansion. The accuracy of models can be affected by the type of printer or the technology used.

3D-printed clear aligners are more precise than thermoformed clear dental aligners because of the prior's increased accuracy, load resistance, and lower deformation **(Tartaglia *et al*., 2021).**

Digital occlusal splint and surgical templates increase accuracy, reliability, and efficiency than a conventional one **(Sandhya *et al*., 2020).**

Only in case of models, both linear and volumetric changes were less in the conventional casts, and digital and 3D-printed models have not yet supplanted conventional models to the point where they are entirely obsolete **(Sruthi, H. and Aravind, K.S. 2023).**

CAPTER THREE

CONCLUSIONS AND SUGGESTIONS

3.1 CONCLUSIONS

- Three-dimensional technologies resulted in an optimized workflow during diagnosis, treatment planning, case monitoring and outcome assessment of any given case and aid in better understanding of diagnosis and treatment planning and provides more accurate results.
- A thorough study of these technologies will allow the orthodontist to optimize their time and knowledge and subsequently upgrade the quality of the provided treatment.
- These systems will continue to evolve to better suit the clinicians' needs, and this will ultimately result in improved patient care.
- The use of advanced technologies require lifelong learning training on new devices, programs, techniques and this may cause additional cost on the services provided.

3.2 SUGGESTIONS

1- Do a clinical study comparing between the conventional and 3D printed appliances.

2- Do a survey about the use of 3D printed orthodontic appliances among Iraqi orthodontist and the feedback of these appliances.

3- Do a survey about the use of 3D technology among Iraqi orthodontist and maxillofacial surgeons.

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