Journal of Chemical Health Risks
www.jchr.org
JCHR (2025) 15(1), 54-61 | ISSN:2251-6727

An Overview on 3D Printing in Orthodontics and Dentofacial Orthopedics

R. Nithin Vaishag, BDS[1], Rahul D. Prabha, MDS, PhD[1*], Sapna Varma N.K, MDS[1], and Ajith V.V, MDS[1]

[1]Department of Orthodontics and Dentofacial Orthopedics, Amrita School of Dentistry, Amrita Vishwa Vidyapeetham, Kochi, Kerala, India

(Received: 16 November 2024 Revised: 20 December 2024 Accepted: 04 January 2025)

KEYWORDS

3D Printing; Print Resin; Intraoral Scanner; Printing Technology

ABSTRACT:

Three- dimensional (3D) printing is a relatively newer addition that is extensively researched and experimented for various applications in orthodontics and orthognathic surgeries. Advances in 3D printing and its applications have been incorporated in various fields of engineering and medicine whereas dentistry to a large extent still relies on subtractive manufacturing in the form of computer-aided design and computer-aided manufacturing (CAD-CAM) to produce crown copings and bridge frameworks. The review aims to present detailed discussion on advances in 3D printing techniques, printing resins and their applications in the field of orthodontics and orthognathic surgery.

1. Introduction

Three-dimensional (3D) printing is a versatile technology for accurate reproduction of 3D objects from digital files [1]. It overcomes the limitations of CAD-CAM and provides more accurate results in less time [2]. The review aims to present detailed discussion on advances in 3D printing techniques and their applications in orthodontics and orthognathic surgery.

History of 3D Printing

Dr. Hideo Kodama developed the first 3D printer prototype device in 1981 by building components layer by layer from resin that could be polymerized by UV light. Chuck Hull was the first to patent stereolithography (SLA) in 1986 and is therefore considered the inventor of 3D printing [3].

Scott Crump, in 1989, founded Stratasys, and developed fused deposition modelling (FDM). Carl Deckard, in 1992, licensed the technology of selective laser melting (SLM). In 2005, Dr. Adrian Bowyer introduced the RepRap 3D printing technology, reimagining additive manufacturing as a low-cost, self-replicating technology [3].

2. 3D Scanners

A physical model is transformed into a digital 3D computer-aided design (CAD) document using 3D scanning technologies. The layout and production of customised objects using additive manufacturing (AM) technologies benefit substantially from this digital output. Through shining a light source onto an object, which include tooth, dental arches, or implants, a 3D scanner can accumulate facts and transmit it to a system's scanning software to supply a 3D STL document [4].

A number of 3D scanners are available for clinical use; iTero®, Trios®, E4D dentist, and Zfx IntraScan being a few. On comparing iTero® with Trios®, the two strategies exhibit no discernible differences in precision but the Trios® scanner shows more accuracy than the iTero® scanner. The iTero® and Trios®, have showed the highest accuracy in horizontal measurements and a present a greater reliability when compared to the other scanners such as the E4D dentist, and Zfx IntraScan [5]. The iTero® scanner used by Invisalign® Technology provides patient comfort while recording dental data by reducing gag, making it more efficient and higher quality of work than conventional procedures [6].

The other type of 3D scanners are the indirect scanners which scan the 3D dental models constructed by recording the patient’s dental impression. On comparing the model scanners with the intraoral scanners, the direct scanning systems showed more precise representation of the scanned tissues when compared to indirect scanning systems [7]. Intraoral scanners can be advised for impressions with and without fixed orthodontic appliances as they exhibit a superior transfer accuracy than cast scanning [8].

Journal of Chemical Health Risks
www.jchr.org
JCHR (2025) 15(1), 54-61 | ISSN:2251-6727

3. 3D Printing Technologies

The four printing technologies used predominantly in dentistry are Stereolithography (SLA), Fused Deposition Modeling (FDM), Digital Light Processing (DLP), and Selective Laser Melting (SLM) [9].

The stereolithography 3D printer consists of a platform where the liquid resin is added in layers of preset thickness and cured with a laser beam reflected from a scanning mirror. The laser beam sectionally cures the polymer resin, a single point at a time, into a solid 3D object of the required shape and dimensions. The single point curing process increases its efficiency but also impacts the time taken to print the object. Similar to SLA printing technique, the Digital light printing technique (DLP) uses projected visible light for curing instead of the laser and cures the liquid polymer layer by layer thus resulting in a faster curing time [9].

The most used method of 3D printing is fused deposition modelling (FDM). It includes a printer platform and a system-controlled print head, a nozzle through which raw material in the form of filament is passed which is then deposited onto the platform where the curing takes place into a solid object using a micromirror device. Selective laser melting uses metal powder that is heated with a laser to just above the melting point in the desired shape to fuse the powder and create a solid form. The printer consists of a build platform on which the melted metal powder is deposited to print the required 3D object [9].

When the FDM printer was used to 3D print plaster models, minor dimensional variations were found between the rapid prototypes and the original plaster models [10]. Compared to FDM and SLA, the PolyJet and DLP techniques were found to be more accurate, with PolyJet having the best accuracy for 3D printed models [11]. The PolyJet replicas of the STL file performed better than the SLA models in terms of trueness but the SLA models showed higher dimensional accuracy [12].

Liquid crystal display (LCD) screen printers are similar to DLP printers and work by sliding entire layers onto a resin container while the curing UV light is emitted from an LCD screen instead of a projector. Compared to the aligners printed with the DLP printer, the aligners printed with the LCD printer had significantly higher values for Martens-Hardness, indentation-modulus and elastic-index [13].

When considering subtractive methods of 3D printing, Computerized numerical control (CNC) machining is a computer-aided milling technique that uses a large block of raw material that is milled along a computer-determined path to create a 3D object. Rapid prototyping (RP), on the other hand, uses computer-aided design software (CAD) to design and manufacture a 3D printed object through additive milling. Since CNC machining requires CAM programming, toolpath programming takes a longer period of time. Unlike CNC machining, the entire RP process runs smoothly with minimal human involvement, and models are produced quickly [14].

4. 3D Printing Resins

The resins used for 3D printing vary for each printing technique and show different properties of accuracy, precision, shelf life, curing time, cytotoxicity, dimensional stability, post cure processing techniques, etc.

Dental LT resin shows better colour stability when exposed to staining from red wine, coffee and tea and subjected to accelerated ageing as compared to Dental SG and Clear resins. This makes Dental LT a reliable resin for use in aesthetic bracket printing [15].

Shape memory polymers (SMPs) are a newer innovation in orthodontic 3D printing and aligners printed with SMPs show an increased overall correction efficiency of 93% which make them highly successful for use in aligner printing [16].

Light-curing acrylic-epoxy hybrid resins were developed by using water-soluble monomers and showed low toxicity on long-term intraoral use. However, the aligners printed with these biocompatible resins were brittle and easily prone to fracture in the middle region [17].

5. Post-Processing of 3D Printed Orthodontic Appliances

Various post-processing techniques are followed to improve the mechanical properties and dimensional stability of the 3D printed appliances.

3D printed dental models made of calcium sulphate showed an improvement in their mechanical properties on treatment with Epsom salt after 3D printing [18].

Rinsing the 3D printed splints with Isopropyl Alcohol can remove the cytotoxic methacrylate monomers within five minutes decreasing the cytotoxic effects of the printed material. However, this process affects the flexural strength of the 3D printed appliance [19].

While evaluating the effects of post-curing on directly printed aligners, the aligners that were not cured were found to undergo significant plastic deformation under loading conditions, while aligners that were cured between 400°C and 800°C for 15 to 20 minutes underwent elastic deformation before fracturing under higher compressive loading between 495N and 666N. Increased compressive strength was also achieved under conditions of shorter curing times and lower temperatures [20].

6. Applications of 3D Printing in Orthodontics

3D Printed Aligners

Direct printing of aligners is one of the newest innovations in the field of clear aligner therapy and has made a great impact on reducing fabrication time, decreasing the number of lab procedures, and generating lesser environmental wastes.

Direct 3D printed aligners show minimal to no difference in their mechanical properties with in-vivo ageing [17]. The orientation of printing during aligner fabrication and the post-curing time does not affect the accuracy of the printed aligners [21].

The direct 3D printing of aligners when compared with its thermoformed counterpart is beneficial to the environment. The lack of vacuum moulds or printing models needed during the direct production process saves time and money. In addition, no cutting is required in this printing process thus producing less waste and reducing carbon emissions [22].

The cytotoxicity of the direct printed aligners when tested with different concentrations of sterile water showed no measurable estrogenicity and no cytotoxic effects [23]. Furthermore, the printed aligner material can withstand immersion in hot water up to 100 °C for 1-2 minutes, which helps in its disinfection [22].

Direct printed aligners have proven to be successful in the treatment of mild to moderate malocclusions and further studies are being explored for their applications in the treatment of complex malocclusions [24].

3D Printed Models

3D printed models with a layer height of 100µm are found to be therapeutically acceptable for treatment outcome assessment, diagnosis and treatment planning, and residency training [25].

The thickness of the 3D printed models significantly affects the accuracy of the orthodontic appliances thermoformed on it. The devices fabricated on 2.0mm models display a higher accuracy when compared to those fabricated on 1.0mm and 1.5mm models [26].

Horizontal stacking of models on the print platform while 3D printing produced dental models which were within clinically acceptable limits and are a practical substitute for orthodontic models, diagnostic purposes and single-unit prosthetic applications [27].

The vacuum formed retainers fabricated on 3D printed models did not significantly differ in the post-treatment stability when compared to the retainers fabricated on conventional stone models. They also showed no differences in stability or quality of life [28].

3D printed models were processed with accelerated aging after post-processing and assessed for dimensional accuracy compared to traditional plaster casts; all the 3D printed models showed mean deviations within the clinical tolerance for all aging exposures. While the plaster casts showed values outside the clinically acceptable range, the printed resin models exhibited dimensional stability during storage [29].

3D printed models irrespective of their resin material and storage conditions remain dimensionally stable for less than seven weeks and need to be immediately used for retainer or appliance fabrication [30].

3D Printed Transfer Trays

In conventional indirect bonding techniques, trays are made in a lab environment either by silicone-mixed or vacuum-formed materials, and brackets are individually positioned on the patient's stone/ resin dental model. The technique does not require physical transfer model as a mediator as the transfer tray can be virtually designed, 3D printed and loaded with brackets for bonding.

High positional accuracy is achieved using CAD-CAM guided bonding devices [30]. When comparing the accuracy between 3D printed and vacuum formed trays,

Journal of Chemical Health Risks
www.jchr.org
JCHR (2025) 15(1), 54-61 | ISSN:2251-6727

though both show better linear than angular control, the 3D printed tray performed more accurately [32].

Comparing the accuracy of bracket placement using the IDB transfer tray after it was produced using tray printing and model printing methods, using the single tray printing approach in the production of IDB trays is recommended due to the lower errors and the ease of production [33]. Bachour et al. revealed that with a high degree of positional accuracy in the three dimensions, the indirect bonding technique using 3D printed trays provides the desired bracket position although the position of the transferred brackets showed a slight taper towards the buccal side [34]. Contradictorily, Hofmann et al. found that while both the traditional silicone tray and the 3D printed IDB tray showed positive results and are applicable for clinical use, the transfer accuracy of the 3D printed tray was not as great [35].

Using a computer-guided 3D printed guide tray for miniscrew insertion, no statistically significant difference was observed in the mini-screw failure rate when compared with freehand placement technique over three months of loading [36].

Indirect bonding using 3D printed IDB trays, however, still remains a technique sensitive field with a high dependence on the experience of the clinician for the success of the care provided [37].

3D Printed Orthodontic Brackets

Comparing the accuracy and functionality of a 3D printed metal bracket in contrast to two commercial bracket systems, Damon and Ti-Orthos, the results showed that the 3D printed slot was more accurate than the control bracket slots and the shear bond strength of the three systems was also comparable [38].

Measuring the frictional resistance (FR), shear bond strength (SBS) and adhesive residual index (ARI) for a customised ceramic bracket and comparing with the values for ceramic brackets available in the market, a statistically insignificant difference in FR and SBS was found between the variables compared while the ARI score was higher for Clarity Advanced brackets. The customised ceramic brackets provided excellent colour and shape matching which were similar to the natural tooth aesthetics, thus making them almost invisible at a social interacting distance [39].

Studying the mechanical properties of 3D printed brackets, 3D printed zirconia brackets prove to be less hard but more fracture resistant than alumina brackets, thus making them beneficial for orthodontic fixed appliance in clinically relevant parameters [40].

3D Printed Orthodontic Retainers

3D printing of the orthodontic retainers allows customisation of the retainers according to the requirements of the patient's occlusion while also reducing the steps required for manufacturing, time spent and might also improve patient compliance.

Use of 3D printed retainers in patients treated for complex malocclusions, revealed good comfort, aesthetics and plaque control in patients after six months, making the 3D printed retainers an effective orthodontic alternative to traditional multifilament stainless steel retainers or fiber-reinforced composite retainers [41].

Comparing the different printing techniques for the manufacture of orthodontic retainers, the stereolithography and polyjet photopolymer printing techniques showed the greatest accuracy while the direct light processing (DLP) and continuous DLP showed higher trueness [42].

Evaluating the bond strength, failure analysis, discoloration, and biodegradation of 3D-printed lingual retainers, significant differences for all tested parameters between the test groups were found with the highest bond strength recorded for the lingual retainers made using a 3D dental pen. This concludes that 3D printed retainers can be used for therapeutic purposes [43].

7. 3D Metal Printing in Orthodontics

Direct metal 3D printing in orthodontics is done using either the direct laser metal sintering or the selective laser sintering technique. The application of direct metal printing in orthodontics is a field that is currently being explored with the simplest to the most complex designs being metal printed and tested for efficiency with conventional appliances. These applications include the 3D printed molar bands which lay over the occlusal surface of the molars not requiring the placement of separators, and 3D printed hyrax-style rapid palatal expanders for transverse expansion of the maxilla [44].

The metal-printed molar distalisation appliances printed using cobalt-chromium alloy showed clinically

Journal of Chemical Health Risks
www.jchr.org
JCHR (2025) 15(1), 54-61 | ISSN:2251-6727

acceptable properties of modulus of elasticity, Martens-Hardness and elastic index but displayed degraded surface oxide layer thus losing resistance to corrosion [45]. Study on the slot precision and torque transmission characteristics of 3D metal printed orthodontic brackets revealed that the 3D printed brackets could express a 60Nm crown torque and had adequate slot accuracy for clinical applications [46]. Larger 3D printed appliances such as Hyrax for maxillary expansion tend to increase stress at the midpalatal suture region when compared to laboratory fabricated appliances [47].

The advantage to customization which is provided by 3D printing metal appliances translates into better treatment efficiency with improved comfort for the patient while seating the appliance, reduced chairside time and improved mechanical and surface properties for the printed appliance [48].

8. 3D Printing in Orthognathic Surgery

3D printed surgical guides are used extensively in the field of orthognathic surgery in the form of initial, intermediate and final occlusal splints. The use of digital surgery planning software along with 3D wafer printing for establishing the required occlusal relationship has resulted in levels of precision comparable to traditional facebow and model surgery [49].

3D printed appliances are also used as piezocision guides and are designed to be translucent for increasing the visibility during the procedure, rigid for improving the support during guidance, and porous in structure for efficient irrigation during the piezocision procedure [50].

Sanchez et al. developed a minimally invasive maxillary expander by using CBCT and CADCAM technologies, two mini-screws and a 3D printed surgical guide. Due to its intrinsic qualities, which included biocompatibility, stiffness, lightness, and resistance to strong palatal disjunction forces, the device could be kept small while still preventing collapse during the procedure. Thus, using digital models, CBCT and CAD/CAM technologies, an effective palatal disjunction device can be easily implanted in a single visit [51].

The customised MARPE appliance developed by Thakkar et al. showed clinically promising results with excellent adaptation and efficient expansion. Though digital fabrication of conventional orthodontic appliances shows comparable results, it is important to weigh the cost- benefit ratio and select cases appropriately for treatment with customised 3D printed appliances [52].

9. Conclusion

3D printing technologies have allowed the clinicians to work with improved efficiency by increasing the accuracy, precision and hence the quality of the appliances fabricated. 3D printing has also been beneficial to the patient by reducing the treatment time and improving the treatment experience.

The applications of 3D printing in orthodontics are numerous and its use in the field of orthognathic surgeries is still being explored for newer possibilities.

Regardless of the slow growing demand, the use of 3D printed appliances in day-to-day practice of orthodontics and orthognathic surgery is eventually going to be inevitable in the near future. Large institutions such as dental colleges and hospitals incorporating 3D printing technologies into their inventory and providing the option of 3D printed appliances as a viable treatment is only the start of a new era in the dental field.

Shape memory is a concept that is used in the technology known as 4D printing. The change in shape is made possible by the incorporation of intelligent materials like hydrogels and polymers. Its application to orthodontics will be revolutionary. The ability to create self-straining wires or self-folding removable appliances can cause the appliances to move continuously, placing and aligning teeth as required. Further studies need to be conducted to explore more applications of 3D and 4D printing in orthodontics and on easier and feasible ways to incorporate the same in daily clinical practice while also keeping in mind to reduce the amount of environmental waste produced.

References

1. Kantaros A, Ganetsos T, Petrescu FI. Three-dimensional printing and 3D scanning: Emerging technologies exhibiting high potential in the field of Cultural Heritage. Applied Sciences. 2023;13(8):4777.
2. Witkowski S, Komine F, Gerds T. Marginal accuracy of titanium copings fabricated by casting and CAD/CAM techniques. J Prosthet Dent. 2006;96(1):47–52.

Journal of Chemical Health Risks

www.jchr.org

JCHR (2025) 15(1), 54-61 | ISSN:2251-6727

3. Su A, Al’Aref SJ. History of 3D printing. In: 3D Printing Applications in Cardiovascular Medicine. Elsevier; 2018:1–10.
4. Taneva E, Kusnoto B, Evans CA. 3D Scanning, Imaging, and Printing in Orthodontics. Issues in Contemporary Orthodontics. 2015.
5. Jung Y-R, Park J-M, Chun Y-S, Lee K-N, Kim M. Accuracy of four different digital intraoral scanners: effects of the presence of orthodontic brackets and wire. Int J Comput Dent. 2016;19(3):203–15.
6. Wang J, Ho V, Kau CH. Orthodontic Management of a Palatal Fistula in a Patient With Pierre Robin Sequence Using 3D Intraoral Scanning and Computer-Aided Design. Cleft Palate-Craniofacial Journal. 2021;58(12):1556–9.
7. Pugalendhi R, Jayaprakasan N, Karuveettil V, Varma NK S, Ajith, D Prabha R. Effectiveness of intraoral scanners in full arch digital impression – a systematic review. Clinical and Investigative Orthodontics. 2022;81(3):127–36.
8. ElNaghy R, Amin SA, Hasanin M. Evaluating the accuracy of intraoral direct digital impressions in 2 infants with unilateral cleft lip and palate compared with digitized conventional impression. Am J Orthod Dentofacial Orthop. 2022;162(3):403–9.
9. Mora S, Pugno NM, Misseroni D. 3D printed architected lattice structures by material jetting. Mater Today. 2022; 59:107–32.
10. Rebong RE, Stewart KT, Utreja A, Ghoneima AA. Accuracy of three-dimensional dental resin models created by fused deposition modeling, stereolithography, and Polyjet prototype technologies: A comparative study. Angle Orthod. 2018;88(3):363.
11. Kim SY, Shin YS, Jung HD, Hwang CJ, Baik HS, Cha JY. Precision and trueness of dental models manufactured with different 3-dimensional printing techniques. American Journal of Orthodontics and Dentofacial Orthopedics. 2018;153(1):144–53.
12. Dietrich CA, Ender A, Baumgartner S, Mehl A. A validation study of reconstructed rapid prototyping models produced by two technologies. Angle Orthodontist. 2017;87(5):782–7.
13. Lo Giudice A, Ronsivalle V, Rustico L, Aboulazm K, Isola G, Palazzo G. Evaluation of the accuracy of orthodontic models prototyped with entry-level LCD-based 3D printers: a study using surface-based superimposition and deviation analysis. Clinical Oral Investigations 2022;26(1):303-12.
14. Martorelli M, Gerbino S, Giudice M, Ausiello P. A comparison between customized clear and removable orthodontic appliances manufactured using RP and CNC techniques. Dent Mater. 2013;29(2).
15. Haynie AS, English JD, Paravina RD, Moon A, Hanigan J, Abu Al Tamn MA, et al. Colour stability of 3D-printed resin orthodontic brackets. J Orthod. 2021;48(3):241–9.
16. Elshazly TM, Keilig L, Alkabani Y, Ghoneima A, Abuzayda M, Talaat S, et al. Primary Evaluation of Shape Recovery of Orthodontic Aligners Fabricated from Shape Memory Polymer (A Typodont Study). Dentistry Journal 2021;9(3):31.
17. Nakano H, Kato R, Kakami C, Okamoto H, Mamada K, Maki K. Development of Biocompatible Resins for 3D Printing of Direct Aligners. Journal of Photopolymer Science and Technology. 2019;32(2):209–16.
18. Ledingham AD, English JD, Akyalcin S, Cozad BE, Ontiveros JC, Kasper FK. Accuracy and mechanical properties of orthodontic models printed 3-dimensionally from calcium sulfate before and after various postprinting treatments. Am J Orthod Dentofacial Orthop. 2016;150(6):1056–62.
19. Xu Y, Xepapadeas AB, Koos B, Geis-Gerstorfer J, Li P, Spintzyk S. Effect of post-rinsing time on the mechanical strength and cytotoxicity of a 3D printed orthodontic splint material. Dent Mater. 2021;37(5):e314–27.
20. Lambart A-L, Xepapadeas AB, Koos B, Li P, Spintzyk S. Rinsing postprocessing procedure of a 3D-printed orthodontic appliance material: Impact of alternative post-rinsing solutions on the roughness, flexural strength and cytotoxicity. Dent Mater. 2022;38(8):1344–53.
21. McCarty MC, Chen SJ, English JD, Kasper F. Effect of print orientation and duration of ultraviolet curing on the dimensional accuracy of a 3-dimensionally printed orthodontic clear aligner design. American Journal of Orthodontics and Dentofacial Orthopedics. 2020;158(6):889–97.
22. Bichu YM, Alwafi A, Liu X, Andrews J, Ludwig B, Bichu AY, et al. Advances in orthodontic clear aligner materials. Bioact Mater. 2023;22:384–403.

23. Pratsinis H, Papageorgiou SN, Panayi N, Iliadi A, Eliades T, Kletsas D. Cytotoxicity and estrogenicity of a novel 3-dimensional printed orthodontic aligner. Am J Orthod Dentofacial Orthop. 2022;162(3):e116–22.
24. Migliorati M, Drago S, Castroflorio T, Pesce P, Battista G, Campobasso A, Gastaldi G, Valvecchi FF, De Mari A. Accuracy of orthodontic movements with 3D printed aligners: A prospective observational pilot study. Korean Journal of Orthodontics. 2024 May 5;54(3):160.
25. Palone M, Longo M, Arveda N, Nacucchi M, De Pascalis F, Spedicato GA, et al. Micro-computed tomography evaluation of general trends in aligner thickness and gap width after thermoforming procedures involving six commercial clear aligners: An in vitro study. Korean J Orthod. 2021;51(2):135–41.
26. Kenning KB, Risinger DC, English JD, Cozad BE, Harris LM, Ontiveros JC, et al. Evaluation of the dimensional accuracy of thermoformed appliances taken from 3D printed models with varied shell thicknesses: An in vitro study. Int Orthod. 2021;19(1):137–46.
27. Hartley O, Shanbhag T, Smith D, Grimm A, Salameh Z, Tadakamadla SK, et al. The Effect of Stacking on the Accuracy of 3D-Printed Full-Arch Dental Models. Polymers (Basel). 2022;14(24).
28. MohdTahir N, Wan Hassan WN, Saub R. Comparing retainers constructed on conventional stone models and on 3D printed models: A randomized crossover clinical study. Eur J Orthod. 2019;41(4):370–80.
29. Hanson MS, Cozad BE, English JD, Kasper FK. Effects of accelerated aging on 3D-printed orthodontic model accuracy. J Clin Orthod. 2022;56(7):413–8.
30. Knode V, Ludwig B, Hamadeh S, Pandis N, Fleming PS. An in vitro comparison of the dimensional stability of four 3D-printed models under various storage conditions. Angle Orthod. 2024;94(3):346–52.
31. Xue C, Xu H, Guo Y, Xu L, Dhami Y, Wang H, et al. Accurate bracket placement using a computer-aided design and computer-aided manufacturing–guided bonding device: An in vivo study. American Journal of Orthodontics and Dentofacial Orthopedics. 2020;157(2):269–77.
32. Niu Y, Zeng Y, Zhang Z, Xu W, Xiao L. Comparison of the transfer accuracy of two digital indirect bonding trays for labial bracket bonding. Angle Orthod. 2021;91(1):67–73.
33. Yoo SH, Choi SH, Kim KM, Lee KJ, Kim YJ, Yu JH, et al. Accuracy of 3-dimensional printed bracket transfer tray using an in-office indirect bonding system. American Journal of Orthodontics and Dentofacial Orthopedics. 2022;162(1):93-102.e1.
34. Bachour PC, Klabunde R, Grünheid T. Transfer accuracy of 3D-printed trays for indirect bonding of orthodontic brackets. Angle Orthod. 2022;92(3):372–9
35. Hofmann EC, Süpple J, von Glasenapp J, Jost-Brinkmann PG, Koch PJ. Indirect bonding: an in-vitro comparison of a Polyjet printed versus a conventional silicone transfer tray. Angle Orthod. 2022;92(6):728–37.
36. Aboshady H, Mohamed A, Abouelezz A, Hamdy M, Fotouh A, Aly S, et al. Failure Rate of Orthodontic Mini-screw after Insertion using 3D Printed Guide versus Conventional Free Hand Placement Technique: Split Mouth Randomized Clinical Trial. Open Access Maced J Med Sci. 2022;10(D):6–13.
37. Sabbagh H, Hoffmann L, Wichelhaus A, Kessler A. Influence of the design of 3D-printed indirect bonding trays and experience of the clinician on the accuracy of bracket placement. J Orofac Orthop 2024.
38. Jackson CB, Ko CC, Hershey HG, Stevens C. Accuracy and Performance of a Novel 3D Metal Printed Orthodontic Bracket. 2017
39. Yang L, Yin G, Liao X, Yin X, Ye N. A novel customized ceramic bracket for esthetic orthodontics: in vitro study. Prog Orthod. 2019;20(1):1-10.
40. Polychronis G, Papageorgiou SN, Riollo CS, Panayi N, Zinelis S, Eliades T. Fracture toughness and hardness of in-office, 3D-printed ceramic brackets. Orthod Craniofac Res. 2023;(1):17
41. Doldo T, Di Vece L, Cagidiaco EF, Nuti N, Parrini S, Carboncini F, et al. A new generation of orthodontic retainer using 3D printing technology: Report of two cases. Journal of Osseointegration. 2018;10(4):142–8.
42. Naeem OA, Bencharit S, Yang IH, Stilianoudakis SC, Carrico C, Tüfekçi E. Comparison of 3-dimensional printing technologies on the precision,

trueness, and accuracy of printed retainers. American Journal of Orthodontics and Dentofacial Orthopedics. 2022;161(4):582–91.
43. Aksakalli S, Ok U, Temel C, Mansuroglu DS, Sahin YM. The mechanical testing and performance analysis of three-dimensionally produced lingual retainers. J World Fed Orthod. 2023;12(2):64–71.
44. Shannon T, Groth C. Be your own manufacturer: 3D printing intraoral appliances. Semin Orthod. 2021;27(3):184–8.
45. Zinelis S, Polychronis G, Papadopoulos F, Kokkinos C, Economou A, Panayi N, et al. Mechanical and electrochemical characterization of 3D printed orthodontic metallic appliances after in vivo ageing. Dental Materials. 2022;38(11):1721–7.
46. Bauer, C.A.J., Scheurer M, Bourauel C, Kretzer JP, Roser CJ, Lux CJ, et al. Precision of slot widths and torque transmission of in-office 3D printed brackets: An in vitro study. Journal of Orofacial Orthopedics. 2023.
47. Bocklet M, Ahmadi F, Tremont T, Ross L, Yao H, Andrade I Jr. Comparison of 3D-printed and laboratory-fabricated Hyrax on stress distribution and displacement of the maxillary complex: a 3D finite element study. Prog Orthod. 2024;25(1).
48. Graf S, Thakkar D, Hansa I, Muthuswamy Pandian S, Adel SM. 3D Metal Printing in Orthodontics: Current trends, Biomaterials, Workflows and Clinical Implications. Semin Orthod. 2023;29(1):34–42.
49. Lee UL, Kwon JS, Choi YJ. Keyhole System: A Computer-Assisted Designed and Computer-Assisted Manufactured Maxillomandibular Complex Repositioner in Orthognathic Surgery. Journal of Oral and Maxillofacial Surgery. 2015;73(10):2024–9.
50. Hou HY, Li CH, Chen MC, Lin PY, Liu WC, Cathy Tsai YW, et al. A novel 3D-printed computer-assisted piezocision guide for surgically facilitated orthodontics. American Journal of Orthodontics and Dentofacial Orthopedics. 2019;155(4):584–91.
51. Sánchez-Riofrío D, Viñas MJ, Ustrell-Torrent JM. CBCT and CAD-CAM technology to design a minimally invasive maxillary expander. BMC Oral Health. 2020;20(1):1–7.
52. Thakkar D, Ghosh A, Keshwani T. Digital workflow for CBCT-guided customized miniscrew-assisted rapid palatal expansion (3D digital MARPE): A clinical innovation. J Indian Orthod Soc. 2020;54(3):262–6.