Submitted: 31 January, 2024 Accepted: 28 May, 2024 Published: 03 September, 2024 DOI:10.22514/jocpd.2024.099

Journal of Clinical Pediatric Dentistry

REVIEW

Current applications of three-dimensional (3D) printing in pediatric dentistry: a literature review

Nagehan Aktaş[1,*,†], Volkan Ciftci[2,†]

[1] Department of Pediatric Dentistry, Faculty of Dentistry, Gazi University, 06490 Ankara, Türkiye
[2] Department of Pediatric Dentistry, Faculty of Dentistry, Çukurova University, 01330 Adana, Türkiye

***Correspondence**
nagehanaktas@gazi.edu.tr;
nagehanduygu@gmail.com
(Nagehan Aktaş)

† These authors contributed equally.

Abstract

Advancements in 3D printing technology are providing a new direction in pediatric dentistry by offering innovative solutions to traditional challenges. The remarkable expansion of 3D printing necessitates a comprehensive examination of its status and applications in the dental field, particularly in the pediatric dentistry. This review provides a comprehensive exploration of the applications of 3D printing in pediatric dental practices by drawing from a systematic search across databases, including PubMed/MEDLINE, Scopus, Web of Science, Scielo and the Cochrane Library. The search strategy employed a combination of keywords: "Digital dentistry and 3D printing", "3D printing technology in dentistry", "3D printing in pediatric dentistry" and "3D printing in pediatric dental procedures". The review encompasses a wide array of studies, including original research, cross-sectional analyses, case reports and reviews. A detailed overview is presented in regard to the use of 3D printing for master and educational models, space maintainers, prosthetic restorations, surgical guide, splint design and fracture treatment, fluoride application, autogenous dental transplantation, anterior teeth restoration, and pediatric endodontics and regenerative treatments. This review shows that 3D printing improves clinical outcomes through personalized and precise treatment options and enhances dental students' educational landscape. Areas lacking extensive research were also identified, which warrent further investigation to optimize the integration of 3D printing in pediatric dentistry. By mapping out the current landscape and future directions, the aim of this paper is to support pediatric dentists in recognizing the broad implications of 3D printing for improving patient care and advancing dental education.

Keywords

3D printing; Additive manufacturing; Dental technology advancements; Digital dentistry; Pediatric dentistry

1. Introduction

There have been significant advances in the integration of computer-aided design (CAD) and computer-aided manufacturing (CAM) in dentistry, which have ushered in digitization and automation in numerous procedures. Until recently, the CAM in dentistry has been synonymous with subtractive manufacturing (SM), where an object is crafted from a solid block or disk through milling, drilling, grinding or other methods. However, this approach has some drawbacks. For example, the material loss can reach up to 90%, it is not capable of producing complex geometries and the number of objects it can produce is limited [1, 2].

Additive manufacturing (AM) is an increasingly prominent alternative way of using CAD files for dental applications. Often this process is described as three-dimensional (3D) printing and is synonymous with rapid prototyping. Unlike traditional methods, this process constructs objects by incrementally adding material layers to create complex structures and ensures minimum material wastage [3]. The surface resolution of objects fabricated using additive manufacturing technology can also be smoother than with subtractive manufacturing because objects are generally formed by depositing layers in the range of 10–20 μm. Thus, additive manufacturing has the capability to overcome several of the constraints of subtractive manufacturing techniques [4].

The basis of 3D printing in dentistry lies in the detailed representation of an object within a 3D CAD file. The object is usually encoded in the STL (Standard Transformation Language, Surface Tessellation Language, or Standard Triangulation Language) file format for printing. This format utilizes triangulation (tessellation) to describe the surface of 3D objects, with each triangle defined by its vertices and surface normal. Increasing the number of triangular facets increases the resolution of the object's surface representation [2].

The main workflow of additive manufacturing technology encompasses four critical steps: data acquisition, data processing, material selection, and the printing process. Data acquisition, and processing involve constructing a digital model, which is typically achieved through various CAD software applications. A computing system is employed to refine the acquired 3D data in reconstruction software. The scanned data is imported in the DICOM (Digital Imaging and Communications in Medicine) format is imported into specialized software platforms like Mimics and Geomagic for further analyses [5]. An appropriate material and manufacturing technique must be chosen for the digital representation. This workflow is adaptable across various printing technologies and accommodates a wide variety of materials, including polymers (polylactic acid, polycaprolactone and polyetheretherketone (PEEK)), metals (stainless steel, cobalt chromium alloy, and titanium and titanium alloy), and ceramics (zirconia) [6, 7].

2. 3D printing technologies in dentistry

Additive manufacturing in dentistry encompasses a variety of printing methods with unique mechanisms. These include stereolithography (SLA), selective laser sintering (SLS), digital light processing (DLP), fused deposition modeling (FDM), polyjet printing and bioprinting. Each technique offers distinct advantages and is selected based on specific requirements of the dental application [2, 6].

SLA is the most popular 3D printing technique in dental applications due to its exceptional precision and resolution. SLA consecutively deposits photosensitive resins in layers, which are then polymerized to construct the desired structure. In dental practices, SLA predominantly fabricates resin-based entities, including provisional crowns, resin prosthetic teeth, removable dentures, and mouth guards [8]. Both SLS and SLA employ laser technology to scan and build the object using powder-based material in case of SLS and liquid resin for SLA [6]. DLP printers resemble SLA in functionality but are differentiated by their utilization of visible light-reactive materials, which can expedite the printing process and are compatible with a broader wavelength spectrum. DLP printers are frequently employed to produce resinous and wax-mimetic substances for casting purposes and the creation of dental models [9, 10].

FDM involves extruding heated material that solidifies upon deposition, with successive layers fusing together to form the final object. Polyjet printing creates a 3D model by jetting ultraviolet light-curable polymer in a single layer and has the capability of producing varying densities, elasticities, and resolutions. Bioprinting has found a niche within tissue engineering and uses cell inks in bioprinters and micro-tissue systems to fabricate biological structures [3].

3. Applications of 3D printing in pediatric dentistry

Digital technology is an important part of contemporary dental practice in today. The inclusion of artificial intelligence (AI) is a new trend in digital dentistry and allows many procedures to be performed [11]. In recent years, the application of 3D printing technology has gained popularity and has seen a rapid escalation in potential across a broad spectrum of dental fields. Its adoption has been particularly notable in oral and maxillofacial surgery, prosthodontics, and orthodontics, where 3D printing has surged. In these fields, 3D-printed technology has become preferred as an alternative to conventional applications [6, 12]. However, it is worth noting that the use of these systems in pediatric dentistry is still limited and needs to be investigated.

The management of pediatric dental patients presents considerable obstacles for dentists as children often have considerable fear and anxiety regarding dental procedures. Consequently, it is unrealistic to anticipate the same level of cooperation from young patients as that expected from adults. Thus, pediatric dentistry is evolving, and there is an emphasis on developing more effective and efficient approaches to fulfill the unique needs and considerations of children. Among the numerous technological advancements, 3D printing has notably risen in prominence in pediatric dentistry recently. Known for its precision and accuracy, 3D printing offers a less invasive approach, and it has been reported that it can also provide an advantage of reducing chair-side time, which is a significant advantage in the treatment of pediatric patients [13–15].

3.1 Master models

With the use of intraoral scanners, dentists often prefer to utilize a 3D-printed master model of the scanned jaw (Fig. 1). The production of a master model is not always necessary, but this preference persists due to dentists' familiarity and comfort with visualizing restorations on a physical model, in spite of their direct digital fabrication. Moreover, the digital archiving of patient model data allows for on-demand printing, which significantly alleviates the burden of physical storage [16].

3.2 Educational models

Recent advancements in 3D printing technologies have enabled the development of innovative educational and clinical instruments in dental education. Integrating 3D scanners, cone-beam computed tomography (CBCT), and 3D printers has revolutionized the creation of anatomically accurate replicas, yielding simulated dental models with a high degree of clinical relevance. These models have proven to be effective tools in education and have enhanced the learning experience [17–19].

The increased accessibility of 3D printing equipment has significantly improved the prospects of employing 3D-printed educational models for dental professionals. The aim in this regard is primarily to augment dental students' hands-on skills and substantially improve dental practitioners' practical competencies [17, 20–22]. Studies using 3D models in undergraduate and graduate education in dentistry have been carried out in the fields of prosthetics [21, 23–25], surgery [12, 26–28], endodontics [29, 30], pediatric dentistry [17], and trauma management [31].

Marty *et al.* [17] designed and produced a 3D model from a computed tomography (CT) scan, which has been the only 3D-printed model for pediatric dentistry training thus far. Students prepared pulpotomy and stainless-steel crowns on primary

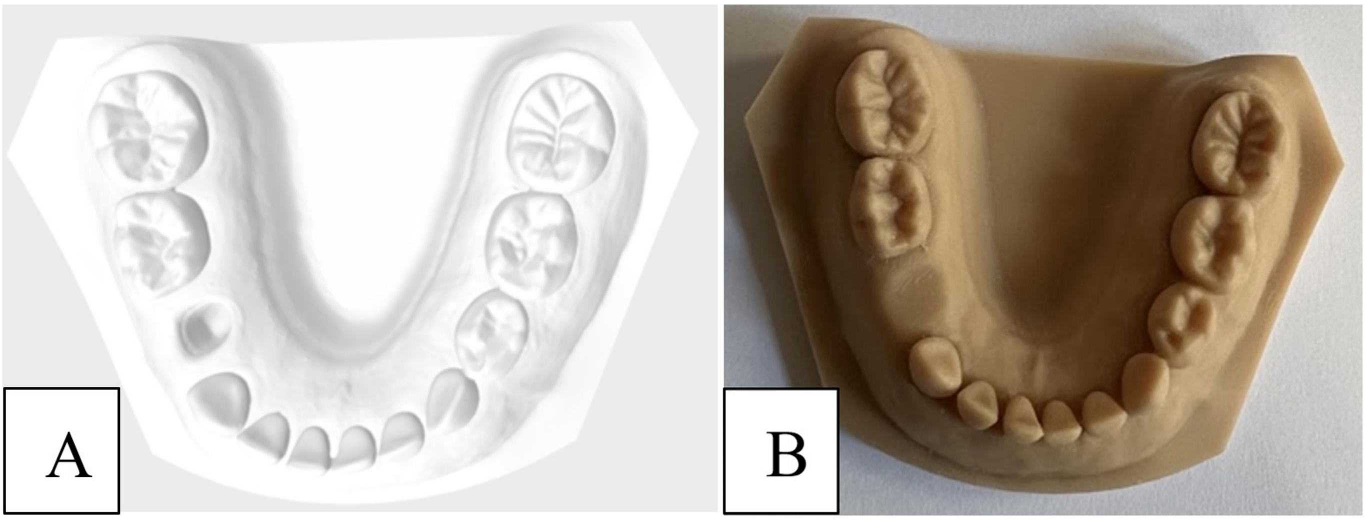

FIGURE 1. Master models. (A) Digital impression obtained by using intraoral scanners (Trios 5, 3Shape, Copenhagen, Denmark). (B) 3D-printed master model produced with SLA technology (Formlabs Form 3B; Formlabs Inc, Sommerville, MA) and model resin.

molars using industrial and 3D-printed models. While students gave both models high marks regarding learning potential and applicability, the simulation of caries in 3D models was appreciated. Students also reported that 3D models offered a more realistic experience because proximity to the pulp made it possible to understand the need for pulp treatment, which provided an educational advantage [17].

3.3 Fabrication of space maintainers

3D printing is already used in the production of space maintainers in pediatric dentistry [32] (Fig. 2). Dhanotra *et al.* [33] reported that space maintainers fabricated through CAD-CAM or 3D printing methodologies using biocompatible substances, which are referred to as "Digital Space Maintainers". They posited that digitally created space maintainers could be used as alternatives to conventionally produce space maintainers. The authors pointed out that the advantages of digitally fabricated space maintainers include high strength, smooth surfaces, quick fabrication time, light weight, and do not cause gingival trauma [33].

Pawar [34] and Khanna *et al.* [35] used 3D printing to produce space maintainers using titanium-based powdered metal material, which provided maximum precision with the least possible errors compared to conventional band-and-loop space maintainers Tokuç and Yılmaz [36] evaluated the band fit of metal 3D-printed space maintainers using SLS technology. They reported no significant difference in the fit of conventional and 3D-printed metal band-and-loop space maintainers. Although space maintainers produced from printable metal powder materials such as CoCr and titanium alloys seem suitable for clinical use, these materials were reported to be hard, inflexible and unesthetic.

Watson *et al.* [37] assessed the retention properties of 3D-printed space maintainers crafted from various clear resin materials. Their findings revealed that the strength under load of claw-design 3D-printed space maintainers might be sufficient to serve as an alternative to conventional space maintainers. However, they noted lower retention in the 3D-printed space maintainers than conventional ones.

Yangdol *et al.* [32] produced band and loop space maintainers using 3D printing technology in a child with autism. Cobalt-chromium alloy was used in the production of the space maintainer because it is a more cost-effective biomaterial than titanium. The authors reported that it is beneficial for children in need of special health care, considering the advantages of reducing the time spent at the bedside, using fewer tools, and fast and easy production.

Cengiz and Karayılmaz [38] conducted an *in-vivo* study to compare the clinical success, retention, and periodontal effect of conventional band-and-loop space maintainers with 3D-printed space maintainers produced from titanium-based metal powder with SLS. That survival time was significantly higher with conventional space maintainers, and there were no differences between baseline and control values in both groups in terms of gingival and plaque indexes. Additionally, 3D printing has been used in the creation of various interceptive orthodontic appliances, including brackets and clear aligners. It has been reported that 3D printing applications will be significantly beneficial in the fields of early orthodontic applications [39, 40].

3.4 Prosthetic restorations

Recently, in pediatric dentistry, 3D printing has become widespread in the production of esthetic pediatric dental crowns (Fig. 3) [41–45]. The American Academy of Pediatric Dentistry (AAPD) recommends the application of full-coverage restorations for children exhibiting extensive multi-surface lesions or at high risk for caries [46]. The most frequently used restoration has been preformed stainless-steel crown. However, prefabricated zirconia crowns have emerged as a notable alternative for restoring primary molars, which offer enhanced esthetics and clinical performance. Despite these advantages, high cost and wear characteristics have limited their usage [44, 47].

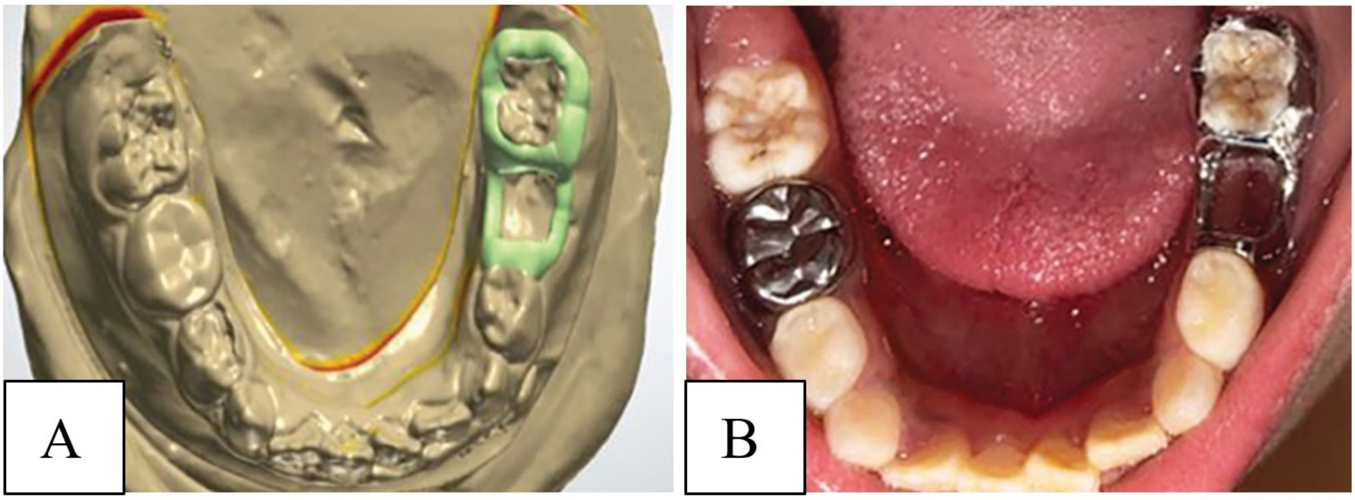

FIGURE 2. 3D-printed space maintainers. (A) The digital design of 3D-printed space maintainer [32]. (B) 3D-printed space maintainer produced with cobalt chromium-based powdered metal material [32].

FIGURE 3. Prosthetic restorations unpolished 3D-printed restoration for primary molars using a 3D printer (Formlabs Form 3B; Formlabs Inc, Sommerville, MA, USA) and printed resin material for definitive prostheses (Formlabs, Formlabs Inc, Sommerville, MA, USA).

Kessler *et al.* [41] evaluated experimental pediatric composite crowns manufactured industrially using 3D printing. The study compared the wear and fracture behaviors of these resin crowns with those of stainless steel and prefabricated zirconia crowns. The findings indicated that the resin crowns exhibited the lowest fracture rates. Al-Halabi *et al.* [42] assessed the clinical performance of crowns for primary molar restorations manufactured using 3D printing and CAD-CAM. The researchers reported that crowns produced with 3D printing displayed superior retention and gingival response, suggesting their reliability and efficacy for restoring primary molars. Al-Halabi *et al.* [43] later compared the clinical performance of 3D-printed crowns with direct composite celluloid crowns in primary molar restorations. Both restorations offered suitable esthetic alternatives, but the 3D-printed crowns exhibited greater marginal integrity and superior gingival health.

Kim *et al.* [44] evaluated the flexural strength and fracture resistance of 3D-printed crowns of varying thicknesses for the esthetic restoration of primary molars in comparison with prefabricated zirconia crowns. The findings indicated that the 3D-printed crowns had clinically comparable fracture resistance and flexural strength to that of zirconia crowns, allowing them to be a new potential esthetic alternative for the restoration of primary molars. Shin *et al.* [48] investigated the wear characteristics of primary tooth enamel and the material surface following mastication simulation using four different temporary composite resins employed in additive manufacturing. They found that the wear behavior varied among the different materials used.

Aydın and Uğuz [49] evaluated the shear bond strength of permanent 3D-printed resin to primary tooth dentin using different bonding agents. The shear bond strength values of the newly developed permanent 3D-printed resin were similar to that of primary teeth dentin with resin-modified glass-ionomer cement and self-adhesive resin cement, but glass-ionomer cement showed lower values than the others.

Aktaş *et al.* [50] evaluated the marginal and internal gaps of resin-based milled and 3D-printed crowns for primary teeth designed with CAD and artificial intelligence software using microcomputed tomography. The tested group 3D-printed resin-based crowns showed clinically acceptable marginal and internal adaptation values. The AI-designed crowns showed better marginal adaptation with 3D printing.

3.5 Surgical guides and obturators

In pediatric dentistry, 3D printing has shown significant promise for accurate diagnosis and treatment planning. Additive manufacturing allows for creating precise 3D models tailored to orofacial defects that could aid in pre-surgical planning and the development of surgical guides. These models are beneficial in pediatric cases and assist in visualizing maxillofacial defects and implant placement. 3D printing has potential for use in pediatric orthognathic surgery but it is essential to note that such surgeries are typically performed on fully grown patients, not pediatric populations [6, 51–54].

In the feasibility study conducted by Lee *et al.* [52] , the effectiveness of 3D planned surgical guides was evaluated in the extraction of supernumerary teeth using 3D-printed simulation models. The results of the study demonstrated that the use of surgical guides significantly reduced the operation time and minimized the amount of material removed. These findings suggest that the 3D surgical guide technique is a suitable method for minimally invasive surgery, especially in pediatric patients.

Joseph *et al.* [51] employed 3D printing for both diagnosis and treatment in a case involving unerupted maxillary central incisors. CBCT and 3D printing were used in dental treatment planning and execution, which enabled precise determination of the position and pathology of unerupted teeth. This facilitated the evaluation of treatment limitations through anchorage and mechanics, and enhanced patient and parental engagement through clear visualization of the malocclusion.

3D printing has promising potential for future applications in the field of pediatric orthognathic surgery [55]. Temporomandibular joint ankylosis in children is a challenging problem and is usually due to tumors, congenital anomalies or trauma [56, 57]. A significant challenge in orthognathic surgery for young patients is the issue of autorotation of the temporomandibular joint, which can potentially lead to condylar instability. Detailed 3D computed tomography and the preparation of stereolithographic models have allowed the construction of individual prostheses for each patient thanks to the application of 3D-printing [58]. The utilization of a personalized orthognathic surgical guide system, incorporating screws and titanium plates produced through 3D printing addresses concerns by facilitating the precise positioning of the condyle. This innovative approach enhances surgical compatibility and ensures a high level of accuracy [59].

Mao *et al.* [60] compared the surgical method and safety of bilateral mandibular distraction osteogenesis using 3D printing and conventionally manufactured surgical guides for the treatment of infants with severe Pierre Robin sequence. 3D-printed surgical guides have been used successfully and show superior effectiveness and safety compared to conventional guides in many regards, such as hospital stay and surgery time [60]. In the context of orthognathic surgery, 3D printing is playing a crucial role in various aspects, including 3D diagnosis, virtual planning, and the creation of surgical guides. While surgical guides are valuable tools, it is important to recognize that they may not always be necessary for optimal outcomes in oral surgery.

The clinical application of an obturator is significantly limited due to patients with large oronasal fistula discomfort in impression taking and difficulties in prosthesis fabrication. Digital technology such as intraoral scanning and additive manufacturing has been applied in dentistry to improve the fabrication of obturators for patients with oronasal fistula clefts. Digital obturators are produced by 3D printing method from models obtained by more precise and accurate impression procedures such as intraoral scanning or CBCT. These digital techniques have many advantages, such as avoiding the inevitable errors associated with the impressions and plaster revisions [61]. Digital obturators can be produced using 3D printing to perfectly adapt to any tissue defect and in a much shorter time [62]. It has been reported that polymethylmethacrylate is widely used as a 3D-printed material in obturators due to its low density, aesthetics, cost effectiveness, stability and biocompatibility [61, 62].

3.6 Splint design and fracture treatment

The primary objective of a dentoalveolar trauma splint is to maintain injured teeth in a natural position and promote the gradual repair of supporting tissues. Additionally, it serves as a guide for the proper repositioning of teeth. The digital construction of a 3D splint is facilitated by CT scan information, and the resulting splint can be cemented or cured in place in the traumatized region [53].

Managing pediatric fractures poses a significant challenge given the crucial role of patient cooperation in most cases. In addition, fractures are treated differently than in adults. In cases of mild jaw fractures where the displacement is not pronounced, a conservative approach is generally advised. Nonetheless, when there is clear displacement, the necessity for accurate and minimally invasive surgical intervention becomes paramount to mitigate effects on the growth and development of the jaw and the eruption of permanent teeth in pediatric patients. Such interventions are rendered more intricate due to the unique anatomical and physiological properties of children's jawbones, which are notably thin and elastic [63].

In the study presented by Yang *et al.* [64], the normal anatomical form of the mandible was reconstructed in the software program using CT images taken from the maxillofacial region in the management of pediatric patients with mandible fractures. The three-dimensional longitudinal position of the tooth germ was measured, and the length of the titanium plate, the number of screws, the direction and length of the screws were adjusted according to the tooth stretch and fracture line. The plates, which will help position both titanium plates and titanium plates and screws, are produced with 3D printing technology.

Case report, have demonstrated notable benefits in the preoperative workflow with the use of a 3D-printed patient-specific splint, including reduced operative time and minimal trauma to adjacent anatomical structures [65]. Du *et al.* [66] used CAD and 3D printing technologies in the treatment of a pediatric patient with multiple mandibular fractures. They used 3D printing with the aim of preventing injury to tooth germs during the surgical intervention and reported that if facilitated the design and precise placement of titanium plates.

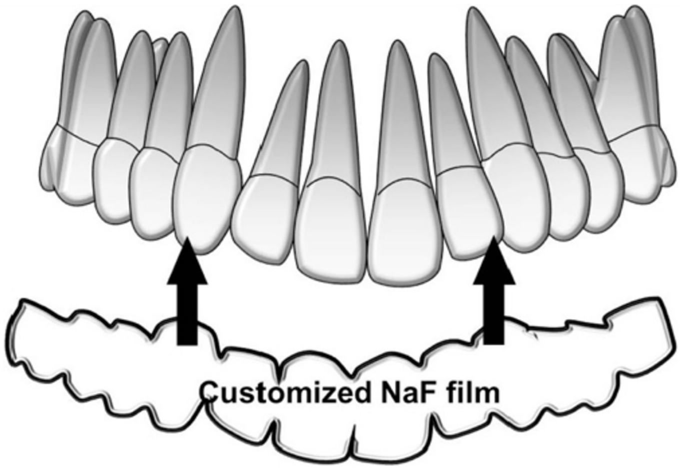

FIGURE 4. Fluoride application Fluoride adhesive film made by 3D printer is attached to the labial/buccal surface of the teeth [67]. NaF: Sodium fluoride.

The authors reported that it is not possible to establish a stable occlusal relationship in children due to incomplete eruption of permanent teeth in the oral cavity of children, short crowns of milk teeth, and root resorption that causes loosening of primary teeth. For this reason, it has been reported that splints and bite plates designed with special software using data obtained from the patient and produced with 3D printing technology can repair the occlusal relationship more accurately, facilitate the restoration of mandibular continuity during surgery, and guide fracture reduction. However, it should be kept in mind that not being able to perform a CT scan beforehand for reduction and fixation may limit the feasibility of using 3D technology in a situation that requires urgent intervention, such as dental trauma [66].

3.7 Fluoride application

The topical application of fluoride faces challenges in maintaining a sufficient concentration in the oral cavity over an extended period as factors like food and continuous saliva flow can wash it away. In response to the limitations of commercially available fluoride formulations, 3D printing is emerging as a potential solution. It allows for the customization of fluoride formulations and enables the creation of a thin film that can be applied to the tooth surface (Fig. 4). This thin film serves as a covering layer that slowly releases fluoride and offers prolonged effectiveness [67].

3.8 Autogenous dental transplantation

Dental autotransplantation has emerged as an integral component of orthodontic surgical treatment for children and adolescents experiencing dental agenesis or non-preservable teeth. In autogenous tooth transplantation, 3D printing can be beneficial by enabling the construction of a new recipient socket with the assistance of a surgical replica of the tooth intended for transplantation. This enables an individualized preparation of the new tooth socket (neo-alveolus) before extraction of the donor tooth is performed. Subsequently, the donor tooth can be placed directly in the neo-alveolus. CBCT provides 3D measurement of the space and tooth dimensions. The tooth is segmented from tomography, and data are obtained as an STL file. 3D printing has enabled the production of biocompatible and sterile dental replicas for use during surgery [68, 69].

A multicenter prospective clinical study by Verveij *et al.* [68] evaluated a facial 3D autotransplantation procedure and analyzed the extra-alveolar time and number of fitting attempts during 3D-guided autotransplantation. The transplantation was performed with an extra-alveolar time of less than 1 minute and an immediate good fit of the donor tooth in most cases. In 4% of cases, the extra-alveolar time exceeded 3 minutes, but this time was within the safe limit for the protection of the periodontal ligament. The authors reported that this may help minimize the risk of damage to the periodontal ligament and prevent subsequent root resorption or ankylosis [68].

It has been reported that the application of 3D technology in pediatric dentistry has facilitated the procedure in autotransplantation. Cahuana-Bartra *et al.* [70] performed a dental transplant on a pediatric patient, and produced a surgical replica of the tooth was produced with 3D printing. The tooth was transferred to the planned location in a short time with a 3D copy and was shown to be successful during follow-up. It has been reported that 3D additive manufacturing technology is a suitable method for creating a copy of a tooth to be transplanted [70]. The use of 3D dental replicas created from radiological data can be a reliable, reproducible, and valid therapeutic solution with a favorable benefit-to-risk balance.

3.9 Anterior teeth restoration

Xia *et al.* [71] described an uncomplicated approach using a 3D-printed template and resin composites to restore and enhance the aesthetic appearance of the anterior tooth. In the presented cases, aesthetic restoration of the central incisors was carried out with the help of a template produced by 3D printing. Expected results were achieved, including appropriate color, tooth anatomy, and translucency of the tooth and the 3D-printed template was reported an acceptable and reliable alternative. The composite injection technique, which offers a complete digital workflow, and in recent case reports, it was used in the restoration of post-orthodontic treatment in the anterior teeth and teeth with microdontia. 3D-printed guides offer a non-invasive approach that can precisely transfer a design made in the software, reducing chair time and simplifying the direct composite restoration procedure [72–74].

3.10 Pediatric endodontics and regenerative treatments

Analyzing a complex root-canal system with obliterated and lateral canals using 2D radiographic images can be challenging. Using 3D-printed models of pediatric patients' root canal architecture derived from digital data from CBCT scans can prove invaluable in treatment planning and access preparation, especially in complex root-canal cases or surgical endodontic procedures like apicoectomy [75, 76]. In this century, the focus in pediatric dentistry will be regenerative endodontics, where additive manufacturing plays a crucial role. It facilitates the delivery of stem cells, the production of biocompatible pulp scaffolds, and the creation of carrier membranes for platelet-rich plasma.

3D printing is instrumental in developing injectable calcium hydroxide molecules, growth factors, and gene therapy for regenerative endodontics. It also aids in the regeneration of the pulp-dentin complex by creating injectable calcium hydroxide molecules, growth factors, and gene therapy. Porous scaffolds developed through 3D printing using calcium hydroxide medicament and calcium phosphate cement can further contribute to the regeneration of the pulp-dentin complex [77, 78].

4. Limitations

Despite the promise of 3D printing, there are inherent limitations to its application in dentistry. These constraints include the resolution limits of the printer, which may affect the intricate details necessary for a precise fit. Material properties can also be a limiting factor as some resins may not yet fully replicate the strength and longevity of conventional materials. The current speed of 3D printing may not be conducive for emergency dental procedures that require immediate turnaround.

This technology has catalyzed a "do-it-yourself trend" and although it is innovative, it introduces potential risks, particularly in medical applications like dentistry. Pursuing self-made dental devices, such as orthodontic braces, carries significant risk due to the absence of professional guidance and the potential to bypass critical testing protocols. Economic considerations also play a role as specialized 3D-printed equipment entails significant investment. Moreover, while the printing process itself might be expedient, the pre- and post-processing stages can be labor and time-intensive, which detracts from the overall efficiency [79]. In a recent study, the high cost of the devices, the need for skilled operators, limited material use, increased manufacturing speed, and decreasing accuracy were reported as the limitations of 3D printing [80].

5. Future perspectives

The use of additive manufacturing in pediatric dentistry is just beginning. Integrating 3D printing technology into pediatric dentistry will advance clinical practice and education.

The potential for further advancements in material science and printing techniques will likely enhance the precision and range of dental applications, ranging from complex orthodontic appliances to intricate prosthetic restorations. More widespread use of biocompatible and sustainable materials may be possible soon, thus providing safer and more environmentally friendly dental solutions. Additionally, the ongoing development of software and digital imaging techniques will streamline the design and manufacturing process, making 3D printing more accessible and cost-effective for dental practices.

In the education sector, 3D printing is poised to revolutionize dental training by offering more realistic and interactive models that closely mimic clinical scenarios. This advancement will not only improve the learning experience for students but also aid in patient education. As research continues to explore the boundaries of 3D printing, its integration into pediatric dentistry is set to evolve and shape a new era of dental care that will be more precise, patient-centric, and educationally enriching.

6. Conclusion

In conclusion, the 3D printing in pediatric dentistry marks a significant advancement in the field. By maximizing precision and minimizing patient discomfort, it will streamline dental procedures and provide a more patient-friendly approach, especially for pediatric patients. It is poised to revolutionize dental practices by offering innovative solutions that align with the evolving needs of both practitioners and patients. Ultimately, the incorporation of 3D printing in pediatric dentistry is set to enhance the quality of patient care, improve treatment outcomes, and enrich the educational experience for upcoming dental professionals.

ABBREVIATIONS

CAD, Computer-Aided Design; CAM, Computer-Aided Manufacturing; SM, subtractive manufacturing; AM, additive manufacturing; 3D, three dimensional; STL, Standard Transformation Language, Surface Tessellation Language, or Standard Triangulation Language; DICOM, Digital Imaging and Communications in Medicine; PEEK, polyetheretherketone; SLA, Stereolithography; SLS, Selective Laser Sintering, DLP, Digital Light Processing; FDM, Fused Deposition Modeling; AI, Artificial Intelligence; CBCT, Cone Beam Computed Tomography; AAPD, The American Academy of Pediatric Dentistry; CT, Computed Tomography.

AVAILABILITY OF DATA AND MATERIALS

The data are contained within this article.

AUTHOR CONTRIBUTIONS

NA—designed the study. NA and VC—wrote the manuscript. All authors contributed to editorial changes in the manuscript. All authors read and approved the final manuscript.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

Not applicable.

ACKNOWLEDGMENT

Not applicable.

FUNDING

This research received no external funding.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

REFERENCES

[1] Strub JR, Rekow ED, Witkowski S. Computer-aided design and fabrication of dental restorations: current systems and future possibilities. Journal of the American Dental Association. 2006; 137: 1289–1296.

[2] Kessler A, Hickel R, Reymus M. 3D printing in dentistry—state of the art. Operative Dentistry. 2020; 45: 30–40.

[3] Balhaddad AA, Garcia IM, Mokeem L, Alsahafi R, Majeed-Saidan A, Albagami HH, *et al*. Three-dimensional (3D) printing in dental practice: applications, areas of interest, and level of evidence. Clinical Oral Investigations. 2023; 27: 2465–2481.

[4] Schweiger J, Beuer F, Stimmelmayr M, Edelhoff D, Magne P, Güth JF. Histo-anatomic 3D printing of dental structures. British Dental Journal. 2016; 221: 555–560.

[5] Kamio T, Suzuki M, Asaumi R, Kawai T. DICOM segmentation and STL creation for 3D printing: a process and software package comparison for osseous anatomy. 3D Printing in Medicine. 2020; 6: 17–29.

[6] Oberoi G, Nitsch S, Edelmayer M, Janjić K, Müller AS, Agis H. 3D printing-encompassing the facets of dentistry. Frontiers in Bioengineering and Biotechnology. 2018; 6: 172–185.

[7] Huang G, Wu L, Hu J, Zhou X, He F, Wan L, *et al*. Main applications and recent research progresses of additive manufacturing in dentistry. BioMed Research International. 2022; 2022: 5530188.

[8] Abduo J, Lyons K, Bennamoun M. Trends in computer-aided manufacturing in prosthodontics: a review of the available streams. International Journal of Dentistry. 2014; 2014: 783948.

[9] Kadry H, Wadnap S, Xu C, Ahsan F. Digital light processing (DLP) 3D-printing technology and photoreactive polymers in fabrication of modified-release tablets. European Journal of Pharmaceutical Sciences. 2019; 135: 60–67.

[10] Sherman SL, Kadioglu O, Currier GF, Kierl JP, Li J. Accuracy of digital light processing printing of 3-dimensional dental models. American Journal of Orthodontics and Dentofacial Orthopedics. 2020; 157: 422–428.

[11] Vishwanathaiah S, Fageeh HN, Khanagar SB, Maganur PC. Artificial intelligence its uses and application in pediatric dentistry: a review. Biomedicines. 2023; 11: 788–809.

[12] Hanisch M, Kroeger E, Dekiff M, Timme M, Kleinheinz J, Dirksen D. 3D-printed surgical training model based on real patient situations for dental education. International Journal of Environmental Research and Public Health. 2020; 17: 2901–2912

[13] Tiwari S, Kulkarni PD, Rathi SV, Abraham JM, Agrawal N, Kumar A. 3D printing: a silver lining in pediatric dentistry. NVEO—Natural Volatiles & Essential Oils Journal. 2021; 18: 11582–11591.

[14] Khan MK. Modern digital pediatric dentistry with the advent of intraoral sensors, computer-aided design/computer-aided manufacturing, and three-dimensional printing technologies: a comprehensive review. Journal of Dental Research and Review. 2022; 9: 195–201.

[15] Dutta S, Gupta S, Isha S, Gumro M, Panwar M. 3D printing—a revolutionary change in pediatric dentistry. European Journal of Dental and Oral Health. 2023; 4: 1–5.

[16] Dawood A, Marti Marti B, Sauret-Jackson V, Darwood A. 3D printing in dentistry. British Dental Journal. 2015; 219: 521–529.

[17] Marty M, Broutin A, Vergnes JN, Vaysse F. Comparison of student's perceptions between 3D-printed models versus series models in paediatric dentistry hands-on session. European Journal of Dental Education. 2019; 23: 68–72.

[18] Panpisut P, Doungkom P, Padunglappisit C, Romalee W, Suksudaj N. Assessment of 3D-printed tooth containing simulated deep caries lesions for practicing selective caries removal: a pilot study. International Journal of Environmental Research and Public Health. 2022; 20: 101.

[19] Petre AE, Pantea M, Drafta S, Imre M, Tâncu AMC, Liciu EM, *et al*. Modular digital and 3D-printed dental models with applicability in dental education. Medicina. 2023; 59: 116–143.

[20] Kröger E, Dekiff M, Dirksen D. 3D-printed simulation models based on real patient situations for hands-on practice. European Journal of Dental Education. 2017; 21: 119–125.

[21] Höhne C, Schmitter M. 3D-printed teeth for the preclinical education of dental students. Journal of Dental Education. 2019; 83: 1100–1106.

[22] Dobroś K, Hajto-Bryk J, Zarzecka J. Application of 3D-printed teeth models in teaching dentistry students: a scoping review. European Journal of Dental Education. 2023; 27: 126–134.

[23] Lin WS, Chou JC, Charette JR, Metz MJ, Harris BT, Choi N. Creating virtual 3-dimensional models for teaching pre-clinical tooth preparation: students' usages and perceptions. European Journal of Dental Education. 2018; 22: 573–581.

[24] Höhne C, Schwarzbauer R, Schmitter M. 3D-printed teeth with enamel and dentin layer for educating dental students in crown preparation. Journal of Dental Education. 2019; 83: 1457–1463.

[25] Höhne C, Dickhaut N, Schmitter M. Introduction of a new teaching concept for dentin post preparation with 3D-printed teeth. European Journal of Dental Education. 2020; 24: 499–506.

[26] Werz SM, Zeichner SJ, Berg BI, Zeilhofer HF, Thieringer F. 3D-printed surgical simulation models as educational tool by maxillofacial surgeons. European Journal of Dental Education. 2018; 22: 500–505.

[27] Chae YK, Lee H, Jih MK, Lee HS, Lee JW, Kim SH, *et al*. Validation of a three-dimensional printed model for training of surgical extraction of supernumerary teeth. European Journal of Dental Education. 2020; 24: 637–643.

[28] Seifert LB, Schnurr B, Herrera-Vizcaino C, Begic A, Thieringer F, Schwarz F, *et al*. 3D-printed patient individualised models versus cadaveric models in an undergraduate oral and maxillofacial surgery curriculum: comparison of students' perceptions. European Journal of Dental Education. 2020; 24: 809–810.

[29] Reymus M, Fotiadou C, Kessler A, Heck K, Hickel R, Diegritz C. 3D-printed replicas for endodontic education. International Endodontic Journal. 2019; 52: 123–130

[30] Hanafi A, Donnermeyer D, Schäfer E, Bürklein S. Perception of a modular 3D print model in undergraduate endodontic education. International Endodontic Journal. 2020; 53: 1007–1016.

[31] Reymus M, Fotiadou C, Hickel R, Diegritz C. 3D-printed model for hands-on training in dental traumatology. International Endodontic Journal. 2018; 51: 1313–1319.

[32] Yangdol P, Kalra N, Tyagi R, Khatri A, Sabherwal P, Goyal T. Three-dimensional printing technology: patient-friendly and time-saving approach for space management in an autistic child in COVID-19 times. International Journal of Clinical Pediatric Dentistry. 2023; 16: 321–326.

[33] Dhanotra KG, Bhatia R. Digitainers-digital space maintainers: a review. International Journal of Clinical Pediatric Dentistry. 2021; 14: 69–75.

[34] Pawar BA. Maintenance of space by innovative three-dimensional-printed band and loop space maintainer. Journal of the Indian Society of Pedodontics and Preventive Dentistry. 2019; 37: 205–208.

[35] Khanna S, Rao D, Panwar S, Pawar BA, Ameen S. 3D-printed band and loop space maintainer: a digital game changer in preventive orthodontics. Journal of Clinical Pediatric Dentistry. 2021; 45: 147–151.

[36] Tokuc M, Yilmaz H. Comparison of fit accuracy between conventional and CAD/CAM-fabricated band-loop space maintainers. International Journal of Paediatric Dentistry. 2022; 32: 764–771.

[37] Watson L, Danley B, Versluis A, Tantbirojn D, Brooks J, Wells MH. A

structural analysis of 3D-printed pediatric space maintainers. Pediatric Dentistry. 2023; 45: 342–347.
[38] Cengiz A, Karayilmaz H. Comparative evaluation of the clinical success of 3D-printed space maintainers and band-loop space maintainers. To be published in International Journal of Paediatric Dentistry. 2024. [Preprint].
[39] Campobasso A, Battista G, Lo Muzio E, Colombo S, Paglia M, Federici Canova F, *et al*. New 3D-printed polymers in orthodontics: a scoping review. European Journal of Paediatric Dentistry. 2023; 24: 224–228.
[40] Aksoy M, Topsakal KG, Bal C, Akdeniz BS, Duran GS. Comparing the physical and mechanical properties of different biocompatible three-dimensional resin materials in possible use of dental appliances: an *in vitro* study. Orthodontics & Craniofacial Research. 2023; 26: 679–686.
[41] Kessler A, Kapor S, Erdelt K, Hickel R, Edelhoff D, Syrek A, *et al*. Two-body wear and fracture behavior of an experimental paediatric composite crown in comparison to zirconia and stainless steel crowns dependent on the cementation mode. Dental Materials. 2021; 37: 264–271.
[42] Al-Halabi MN, Bshara N, Nassar JA, Comisi JC, Rizk CK. Clinical performance of two types of primary molar indirect crowns fabricated by 3D Printer and CAD/CAM for rehabilitation of large carious primary molars. European Journal of Dentistry. 2021; 15: 463–468.
[43] Al-Halabi MN, Bshara N, Nassar JA, Comisi JC, Alawa L. Comparative assessment of novel 3D-printed resin crowns versus direct celluloid crowns in restoring pulp treated primary molars. The Journal of Evidence-Based Dental Practice. 2022; 22: 101664.
[44] Kim N, Kim H, Kim IH, Lee J, Lee KE, Lee HS, *et al*. Novel 3D-printed resin crowns for primary molars: *in vitro* study of fracture resistance, biaxial flexural strength, and dynamic mechanical analysis. Children. 2022; 9: 1445.
[45] Park S, Cho W, Lee H, Bae J, Jeong T, Huh J, *et al*. Strength and surface characteristics of 3D-printed resin crowns for the primary molars. Polymers. 2023; 15: 4241–4253.
[46] American Academy of Pediatric Dentistry. Pediatric restorative dentistry. 2022. Available at: https://www.aapd.org/globalassets/media/policies_guidelines/bp_restorativedent.pdf (Accessed: 20 January 2023).
[47] Ajayakumar LP, Chowdhary N, Reddy VR, Chowdhary R. Use of restorative full crowns made with zirconia in children: a systematic review. International Journal of Clinical Pediatric Dentistry. 2020; 13: 551–558.
[48] Shin Y, Wada K, Tsuchida Y, Ijbara M, Ikeda M, Takahashi H, *et al*. Wear behavior of materials for additive manufacturing after simulated occlusion of deciduous dentition. Journal of the Mechanical Behavior of Biomedical Materials. 2023; 138: 105627.
[49] Aydin N, Uguz HN. Shear bond strength of permanent 3D-printed resin and milled zirconia to primary teeth using different luting agents. American Journal of Dentistry. 2023; 36: 239–245.
[50] Aktaş N, Bani M, Ocak M, Bankoğlu Güngör M. Effects of design software program and manufacturing method on the marginal and internal adaptation of esthetic crowns for primary teeth: a microcomputed tomography evaluation. The Journal of Prosthetic Dentistry. 2024; 131: 519.e1–519.e9.
[51] Joseph JR, Merrett S, Rogers S, Clark P. Use of 3D printing in the planning of a patient with unerupted maxillary central incisors. Journal of Orthodontics. 2021; 48: 183–189.
[52] Lee H, Chae YK, Choi S, Jih MK, Lee JW, Choi SC, et al. Feasibility of a 3D surgical guide technique for impacted supernumerary tooth extraction: A pilot study with 3D printed simulation models. Applied Sciences. 2019; 9: 3905.
[53] Nayar S, Bhuminathan S, Bhat WM. Rapid prototyping and stereolithography in dentistry. Journal of Pharmacy & Bioallied Sciences. 2015; 7: 216–219.
[54] Jeong M, Radomski K, Lopez D, Liu JT, Lee JD, Lee SJ. Materials and applications of 3D printing technology in dentistry: an overview. Dentistry Journal. 2023; 12: 1.
[55] Li B, Shen S, Jiang W, Li J, Jiang T, Xia JJ, *et al*. A new approach of splint-less orthognathic surgery using a personalized orthognathic surgical guide system: a preliminary study. International Journal of Oral and Maxillofacial Surgery. 2017; 46: 1298–1305.
[56] Kaban LB, Bouchard C, Troulis MJ. A protocol for management of temporomandibular joint ankylosis in children. Journal of Oral and Maxillofacial Surgery: Official Journal of the American Association of Oral and Maxillofacial Surgeons. 2009; 67: 1966–1978.
[57] Sporniak-Tutak K, Janiszewska-Olszowska J, Kowalczyk R. Management of temporomandibular ankyloses—compromise or individualization—a literature review. Medical Science Monitor: International Medical Journal of Experimental and Clinical Research. 2011; 17: 111–116.
[58] Zoabi A, Redenski I, Oren D, Kasem A, Zigron A, Daoud S, *et al*. 3D printing and virtual surgical planning in oral and maxillofacial surgery. Journal of Clinical Medicine. 2022; 11: 2385.
[59] Philippe B. Custom-made prefabricated titanium miniplates in Le Fort I osteotomies: principles, procedure and clinical insights. International Journal of Oral and Maxillofacial Surgery. 2013; 42: 1001–1006.
[60] Mao Z, Zhang N, Cui Y. Three-dimensional printing of surgical guides for mandibular distraction osteogenesis in infancy. Medicine. 2019; 98: 14754.
[61] Chen J, Yang R, Shi B, Xu Y, Huang H. Obturator manufacturing for oronasal fistula after cleft palate repair: a review from handicraft to the application of digital techniques. Journal of Functional Biomaterials. 2022; 13: 251.
[62] Kapoor A, Gupta R, Sikri A, Nagaraj A, Sikri J. 3D-printed obturators—an innovative journey. Journal of Family Medicine and Primary Care. 2021; 10: 4594–4597.
[63] Aulisa AG, Marsiolo M, Basiglini L, Aletto C, Giordano M, Falciglia F. Management of open pediatric fractures: Proposal of a new multidisciplinary algorithm. Journal of Clinical Medicine. 2023; 12: 6378.
[64] Yang C, Zhang S, Zhang Y. Three-dimensional-printed splint for use in pediatric mandibular fracture. The Journal of Craniofacial Surgery. 2023; 34: 186–187.
[65] Chakravarthy C, Gupta NC, Patil R. A simplified digital workflow for the treatment of pediatric mandibular fractures using three-dimensional (3D) printed cap splint: a case report. Craniomaxillofacial Trauma & Reconstruction Open. 2019; 3: e67–e70.
[66] Du Y, Yang D, Pang Y, Liu C, Zhang K. Application of CAD and 3D printing in the treatment of pediatric multiple mandible fractures: a case report. Medicine Case Reports and Study Protocols. 2021; 2: e0095.
[67] Lee S. Prospect for 3D printing technology in the medical, dental, and pediatric dental field. Journal of the Korean Academy of Pediatric Dentistry. 2016; 43: 93–108.
[68] Verweij JP, van Westerveld KJH, Anssari Moin D, Mensink G, van Merkesteyn JPR. Autotransplantation with a 3-dimensionally printed replica of the donor tooth minimizes extra-alveolar time and intraoperative fitting attempts: a multicenter prospective study of 100 transplanted teeth. Journal of Oral and Maxillofacial Surgery: Official Journal of the American Association of Oral and Maxillofacial Surgeons. 2020; 78: 35–43.
[69] Debortoli C, Afota F, Lerhe B, Fricain M, Corazza A, Savoldelli C. Autotransplantation with tooth replica: technical note. Journal of Stomatology, Oral and Maxillofacial Surgery. 2023; 124: 101353.
[70] Cahuana-Bartra P, Cahuana-Cárdenas A, Brunet-Llobet L, Ayats-Soler M, Miranda-Rius J, Rivera-Baró A. The use of 3D additive manufacturing technology in autogenous dental transplantation. 3D Printing in Medicine. 2020; 6: 16.
[71] Xia J, Li Y, Cai D, Shi X, Zhao, Jiang Q, *et al*. Direct resin composite restoration of maxillary central incisors using a 3D-printed template: two clinical cases. BMC Oral Health. 2018; 18: 158–164.
[72] Hosaka K, Tichy A, Motoyama Y, Mizutani K, Lai WJ, Kanno Z, *et al*. Post-orthodontic recontouring of anterior teeth using composite injection technique with a digital workflow. Journal of Esthetic and Restorative Dentistry. 2020; 32: 638–644.
[73] Zhang Y, Zhang J, Fan L, Yu H. Closing post-orthodontic spaces between anterior teeth using sequential 3D-printed direct composite injection guides. Operative Dentistry. 2022; 47: 612–619.
[74] Watanabe K, Tichy A, Kamoi K, Hiasa M, Yonekura K, Tanaka E, *et al*. Restoration of a microdont using the resin composite injection technique with a fully digital workflow: a flexible 3D-printed index with a stabilization holder. Operative Dentistry. 2023; 48: 483–489.
[75] Byun C, Kim C, Cho S, Baek SH, Kim G, Kim SG, *et al*. Endodontic

treatment of an anomalous anterior tooth with the aid of a 3-dimensional printed physical tooth model. Journal of Endodontics. 2015; 41: 961–965.
[76] Van Der Meer WJ, Vissink A, Ng YL, Gulabivala K. 3D computer-aided treatment planning in endodontics. Journal of Dentistry. 2016; 45: 67–72.
[77] Murray PE, Garcia-Godoy F, Hargreaves KM. Regenerative endodontics: a review of current status and a call for action. Journal of Endodontics. 2007; 33: 377–390.
[78] Xu HH, Wang P, Wang L, Bao C, Chen Q, Weir MD, *et al*. Calcium phosphate cements for bone engineering and their biological properties. Bone Research. 2017; 5: 17056.
[79] Bhargav A, Sanjairaj V, Rosa V, Feng LW, Fuh Yh J. Applications of additive manufacturing in dentistry: a review. Journal of Biomedical Materials Research: Part B, Applied Biomaterials. 2018; 106: 2058–2064.
[80] Acharya A, Chodankar RN, Patil R, Patil AG. Assessment of knowledge, awareness, and practices toward the use of 3D printing in dentistry among dental practitioners and dental technicians: a cross-sectional study. Journal of Oral Biology and Craniofacial Research. 2023; 13: 253–258.

How to cite this article: Nagehan Aktaş, Volkan Ciftci. Current applications of three-dimensional (3D) printing in pediatric dentistry: a literature review. Journal of Clinical Pediatric Dentistry. 2024; 48(5): 4-13. doi: 10.22514/jocpd.2024.099.