RESEARCH PAPER

3D printing in pediatric dentistry: advancement, application and Future Directions

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ABSTRACT

In recent decades, 3D printing significantly impacted dentistry by improving clinician's skills through realistic training and advanced surgical planning. Integrating 3D printing, CAD-CAM, intra-oral scanning and CBCT data has transformative potential; creating intricate structures for research, treatment planning, training, and instruction. 3D printing and digital dentistry revolutionised dental precision, reducing clinical equipment and chair side time. This extends to complex craniofacial operations, where surgical guides and 3D-printed models enhance accuracy, reduce invasiveness, and improve predictability. Challenges in widespread adoption include a scarcity of trained operators, higher expenses, limited materials, post-processing needs, maintenance, and safety regulations. Ongoing development signals a substantial transformation in dentistry. Unlocking this advancement requires imperative research, especially in regions like India to enhance patient health and wellness through comprehensive approaches to harness the benefits of 3D printing and digital dentistry. The current review focuses on the various applications of 3D printing in the field of pediatric dentistry emphasising on the possibility of adapting digital dentistry in the field.

Keywords: 3D printing, Pediatric dentistry, Digital dentistry, CAD-CAM, Additive manufacturing, Customized dental devices.

How to cite this article: Ajgaonkar S, Shetty AA. 3D printing in pediatric dentistry: advancement, application and Future Directions. Int J Drug Deliv Technol. 2026;16(65s):1235-1243. DOI: 10.25258/ijddt.16.65s.127

INTRODUCTION

Dentistry has evolved significantly over the years, impacting patients' health for both functional and cosmetic reasons. Dentistry in the contemporary era has undergone significant evolution, especially with the advent of digital dentistry a few decades ago, leading to transformative advancements. In 1983, Charles Hull pioneered three-dimensional object creation using stereo lithography. Although Francois Duret introduced digital dentistry in the 1970s, it initially faced resistance and took time to integrate into contemporary practices.[1]

The process of "3D printing" builds objects layer by layer, known as additive manufacturing or rapid prototyping. Customization is now achievable with additive manufacturing (AM). The term "3D printing" is relatively recent but has become popular.[2]

Every restoration or reconstruction that a dentist performs is specific to the patient, their jaw, their tooth, or their implant. These restorations or reconstructions will be intrinsically complicated, necessitating the exact replication of intricate geometry.[3] The precise one-off manufacturing of complex structures in a range of materials with highly desirable qualities for use in surgery and dentistry is where 3D printing excels.[4]

Treating children's dental health poses challenges for dental professionals as young patients often experience heightened fear and anxiety due to emotional immaturity. Unlike adults who understand the seriousness of dental issues, expecting the same level of cooperation from children is unfair.[5]

Pediatric dentistry is evolving to meet the specific needs of young patients more effectively. Recent advancements, such as 3D printing, play a crucial role in improving dental treatment.[6]

HISTORY

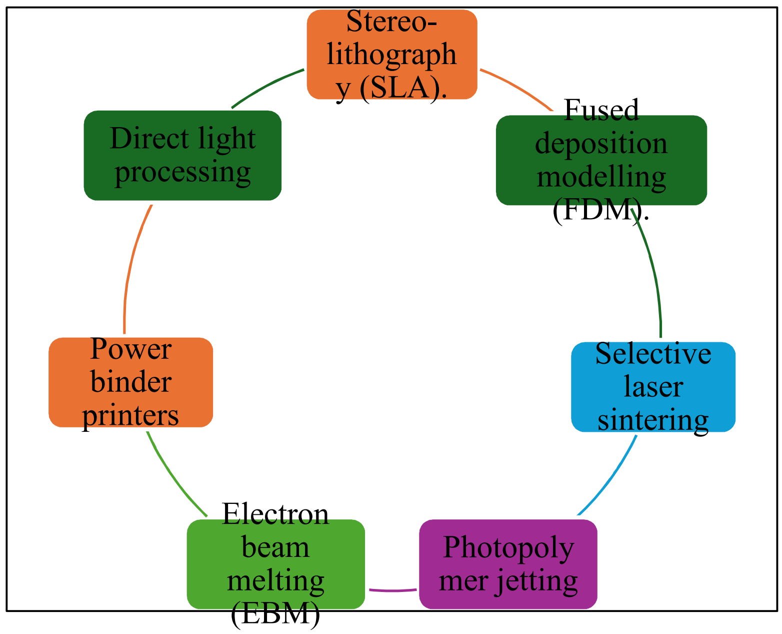
Timeline for the Development of Bioprinting Technology from its inception to the Current State of the Art Year is as follows (table 1):

1984	Charles Hull's invention of stereolithography (SLA) began with 3D printing for the creation of three-dimensional things from digital data.
1988	Cells were micropositioned in two dimensions utilising cytoscribing technology by Klebe et al. Used a typical Hewlett-Packard (HP) inkjet printer
1996	Cells adhered to one another and moved in clusters.
1996	First-time natural biomaterial has been used to regenerate tissue in humans
1996	Gabor Forgacs et al. Determined a quantitative measure of tissue cohesion by concluding that apparent tissue surface tension represented the macroscopic manifestation of molecular adhesion between cells.
1998	Technology for cell sheets was invented.
1999	Direct write laser (LDW)
1999	Odde et al. Used laser assisted bioprinting to deposit living cells in order to create analogues with intricate anatomical features.
2001	First bladder tissue-engineered utilising a synthetic scaffold
2002	Bioprinting made possible Using inkjet technology
2003	Live cells produced using inkjet Printing
2004	Cells dispensed using a modified inkjet printer
2006	3D tissue made entirely of cells without a framework was created
2008	Tissue spheroids used as building blocks as a concept for digital printing
2009	Novogen MMX, the first commercial bioprinter
2009	Scaffold-free vascular constructions
2010	LDW effectively patterns hepatocytes in collagen
2012	In situ skin printing
2012	Restored human articular cartilage Using inkjet technology
2012	Bipolar wave-based drop-on-demand jetting
2012	Extrusion-based (syringe) bioprinting engineering of an artificial liver
2014	Using a multiarm bioprinter to integrate tissue production with printed vasculature
2016	Large-scale bioprinting of porous tissue structures

[Table-1] Chronological milestones in the development of bioprinting and 3D tissue engineering technologies.

TECHNIQUES

In dentistry, additive manufacturing, or 3D printing, is used for a variety of purposes using the following techniques (fig 1):



[Fig-1] : Techniques used in 3D Printing

1. STEREO LITHOGRAPHY

Charles Hull, introduced stereo-lithography, an additive manufacturing technique enabling the creation of parts from computer-aided design (CAD) files. These files specify the size and geometry of the parts, often represented in the STL file format. Contains triangular coordinates forming the surface of the 3D structure; sliced into layers ranging from 25 to 100 mm thick.[7]

The stereolithography apparatus (SLA) employs computed tomography (CT) scanning to verify the accuracy of the process by comparing scan results with the design. The technique involves spatially controlled solidification of liquid resin through photo-polymerization. Photopolymer ingredients like acrylate and resin are used, cured by a UV laser, resulting in layer-by-layer construction.

Printing is managed via digital light projection in a top-down approach. The thickness of the curing layer is crucial, determined by the energy of the light source.[8]

The advantages and limitations of stereolithography are summarised in Table 2

ADVANTAGES	LIMITATIONS
• Precision • Versatility • Processing light-sensitive hydrogels layer by layer	• Lack of suitable biocompatible and biodegradable polymers • Potential harm from residual toxic photocuring reagents • Inability to remove structures entirely • Restriction on horizontal gradients in structures • UV light exposure

[Table 2]: Advantages and limitations of stereolithography (SLA) in bioprinting

2. FUSED DEPOSITION MODELING (FDM)

Introduced by Stratasys in 1990, Fused Deposition Modeling involves layer-by-layer deposition of fused materials and is applied in modeling, prototyping, and production.[9]

It relies on the extrusion process, depositing thermoplastic materials like polymer and synthetic stone to create parts. The printing material is fed to the printing head for the first layer of CAD-modelled components. The printer head moves synchronously in X and Y to deposit the material. Subsequent layers are created by lowering the printer head's base. Once a section is complete, the support material is removed. Commonly used thermoplastics, such as Polycarbonate, Acrylonitrile butadiene styrene, and Polylactic acid, with low melting temperatures, achieve a maximum tensile strength of 1410 N, enhancing fracture toughness.[9]

Some printers utilize a heated bed to prevent warping during cooling, maintaining dimensional accuracy and uniform cooling. Attention to the extruder's design and temperature control is crucial for overall printing accuracy and model quality.[9]

The advantages and limitations of fused deposition modeling are summarised in Table 3

ADVANTAGES	LIMITATIONS
• Inexpensive • Tough and durable • Sustainable • Low cost of fabrication	• Only thermoplastic • Need support structures • Need ventilation • High maintenance cost • Internal anisotrophy

[Table 3]: Advantages and limitations of fused deposition modeling (FDM) in bioprinting

3. SELECTIVE LASER SINTERING (SLS)

Selective Laser Sintering (SLS), an advanced additive manufacturing and rapid prototyping method, can efficiently produce high-quality finished items directly from Stereolithography (STL) or Computer-Aided Design (CAD) files, saving significant time and costs. This allows for the creation of intricate and organic geometries that are typically unattainable with traditional manufacturing methods. Carl Deckard and Joseph Beaman developed SLS in the Department of Mechanical Engineering at the University of Texas at Austin, building upon the liquid curing technology used in 3D printing.[10]

In the SLS process, a rolling mechanism deposits a powder layer on the work area, while a CO2 laser sinters each layer of the powder. The powder is heated to just below the sintering point, and the laser fuses the scanned powder, with the unscanned powder supporting the next layer to prevent distortion. After each layer, a roller applies a new layer of powder. Key factors affecting surface quality and part strength include laser power, temperature, and component orientation.[10]

The advantages and limitations of Selective laser sintering are summarised in Table 4

ADVANTAGES	LIMITATIONS
• Distinguishes itself by producing parts from materials like titanium and nylon	• Resulting part must be post-processed; takes time and involves machining.

• Powder acts as support material on its own doesn't need any further components.	

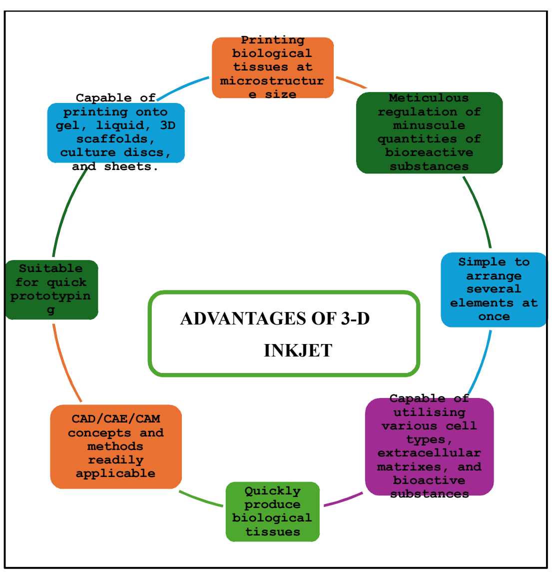
[Table 4]: Advantages and limitations of selective laser sintering (SLS) in bioprinting.

3D INKJET PRINTING

Developed at the Massachusetts Institute of Technology, it involves slicing a 3D model into computer-generated 2D cross-section layers. A layer of powder is applied to the powder bed within a cylinder, and based on computer model data, an inkjet printing head deposits a droplet of binder material onto the powder where solidification is required. The piston descends after each layer, carefully bonding and spreading the powder. Excess powder is removed, and heat treatment strengthens the bonded powder.[11]

The double smoothing (DS) method, employing various layering parameters, disperses dry powder into an ultra-thin intact layer (55 micrometers), eliminating defects and abnormalities in printed objects. This technology is heavily utilized in bone tissue engineering, as illustrated in the figure depicting the operation of 3D inkjet printing.[11]

Figure 2. Schematic representation of the 3D inkjet printing process



[Fig-2]: Schematic representation of the 3D inkjet

USES OF 3-D PRINTING IN PEDIATRIC DENTISTRY

SURGICAL PEDODONTICS

In the era of advanced technological innovation, the integration of 3D printing in dentistry proves instrumental for successful treatment planning and accurate diagnosis. The application of additive manufacturing technology to create 3D printed models facilitates precise visualization of maxillofacial anatomy and aids in pre-operative planning for paediatric dentists. These meticulously crafted 3D models serve as invaluable reference tools during surgery, as demonstrated by Klein et al. (1992).[12,13]

Utilizing CBCT data from paediatric patients, pre-surgical models contribute to the development of surgical stents and guides, particularly beneficial for implant planning and placement.[14] Recent advancements in bone transplant and scaffold printing underscore the significance of 3D printing technology for maxillofacial surgeons. This technology enables the creation of precise, patient-specific three-dimensional scaffolds tailored to specific treatment modalities, including customizable physical properties such as porosity, flexibility, surface roughness, hardness, and solubility.[15,16,17]

The potential impact of 3D printing technology extends to orthodontic surgery, particularly in paediatric patients. Addressing the significant issue of condylar instability during orthognathic surgery, a Personalised Orthognathic Surgical Guide (POSG) system utilizes titanium plates and screws to stabilize the condyle. Through 3D printing technology and CAD-CAM devices, highly accurate, patient-specific titanium plates and screws with superior surgical compatibility can be manufactured.[18,19]

MANAGEMENT OF DENTAL TRAUMA IN YOUNG AND ADOLESCENTS

Accurate stents and 3D printed customised designs are expected to provide reliable long-term outcomes in dental traumatology in the future.

SPLINT DESIGNING

The purpose of a trauma splint is

1. To facilitate the eventual healing of supporting tissues while maintaining damaged teeth or teeth in a position that is almost normal.
2. Serving as a guide to provide appropriate repositioning of the traumatised teeth for the necessary duration of time.

Making such a splint will be made possible by the use of digitally scanned data from a cone beam CT scan. It can then be cured or cemented into the injured area.[20,21]

AUTOTRANSPLANTATION

Implant-based rehabilitation is not possible in the early stages of mixed dentition due to severe dental injuries that cause irreversible tooth loss. Recently, methods for auto transplants have been created with a high success rate. 3D printed templates aid in the establishment of a guided atraumatic strategy in tooth auto-transplantation. This might result in fewer mistakes and better results.[22]

Vandekar et al. utilized 3D printing to scan and reproduce a flawed permanent maxillary central incisor. The replicated tooth served as a quick prototype, guiding the determination of socket size at the recipient site during surgical preparation. This approach preserved the periodontal ligament's viability and allowed for precise positioning. A comparable technique employing 3D printed surgical guidance could be applied in future auto transplant surgeries.[22]

Mandibular fracture reconstruction Contouring bone plates is a labour-intensive and time-consuming procedure that follows treatment for severe mandibular fractures. Three-dimensional printed templates can simplify preoperative preparation for challenging plate contouring and mandibular fracture repair procedures.[23]

In addition to biomimetic scaffolds for bone cell augmentation and tissue development and differentiation, 3D printers may create tailored bone tissue for patients. New 3D printed alginate-peptide hybrid scaffolds can be employed in addition to bone regeneration. Studies claim that scaffolds made of alginate provide a stable environment for the multiplication of stem cells. Scaffolds can be printed using composite powders. To create scaffolds that can be used for bone augmentation, calcium phosphate (Ca3PO4)2 powders can be mixed with a calcium sulphate (CaSO4)-based 3D printing (3DP) powder.[24]

PEDIATRIC REHABILITATION

This century, rehabilitation ought to be the primary priority. However, for a child with a TMJ problem or other orofacial deformity, a young patient, or a youngster who is mentally and physically challenged, the rehabilitation procedure can occasionally become extremely time-consuming, laborious, and physically and psychologically stressful.[25,26] To create an effective maxillofacial prosthesis for orofacial abnormalities, a multi-step procedure and highly qualified dental professionals could be needed.[27] With the current developments in digital dentistry, maxillofacial prosthetics can now be printed straight from the digital data process using intra-oral scanners, CAD-CAM equipment, and 3D printing technology, all without causing damage to young patients or children with special needs.[28]

According to recent research, the physical characteristics of ceramic prosthesis made with the lithography technique are comparable to those of traditional milled ceramics.[24] Research has demonstrated that selective laser melting and electron beam melting may be used to successfully create 3D printed metal implant prostheses.[29] Interim resin restorations made using 3D printing technology and metal crowns exhibit a precise marginal fit, matching the quality of traditionally constructed restorations.[30]

ORTHODONTICS FOR YOUNG AND ADOLESCENTS

3D printing technology has the potential to be a game-changer for patient diagnostics, treatment planning, and—most importantly—motivation in the near future. Patients can now be shown face alterations virtually thanks to 3D printing technology and artificial intelligence software. The patient is able to feel and see the three-dimensional representations of their hand's precise modifications and straightened arches.[31]

Patients can get individualised transparent aligners or braces with precise torque and tip thanks to stereolithography.[32] Results from a recent study by Reynolds et al. using an implanted marker to measure mandibular growth were consistent with Bjork's research on the subject. This will enable the paediatric surgeons do craniofacial surgery by enabling them to work with 3D printed growth models and an orthodontist.[33]

Young patients with TMJ dysfunction can benefit from a personalised splint made possible by additive printing technology.[34] It will be feasible to 3D build exact myofunctional appliances, such as the Herbst, Activator, and twin block appliances, for growing patients based on their specific demands in the near future. Better intraoral fit can be achieved with these precise myofunctional appliances, improving patient compliance and treatment outcomes. 3D printing can also be used to create obturators, feeding appliances for those with cleft lip and palate, and appliances for sleep apnea.[35,36]

PEDIATRIC ENDODONTICS

Examining a complex root canal system with destroyed channels and lateral canals can be challenging using 2D radiography pictures. When the root canal system is obliterated due to fast dentinogenesis and dystrophic calcification, a specially-designed endodontic guide is constructed through 3D digital planning to predictably navigate the obliterated pulp. This preventive measure reduces the risk of iatrogenic root injury, lowering the likelihood of severe dentine destruction or root perforation.[37]

Utilizing digital data from the patient's CBCT scan, 3D printed models of their root canal architecture can be created, proving highly valuable for treatment planning and access preparation. This application extends to surgical endodontic procedures such as apicoectomy.[38]

Stem cell delivery, the creation of biocompatible pulp scaffolds, and PRP carrier membranes will all be accomplished by additive manufacturing. Injectable calcium hydroxide molecules, growth factors, and gene therapy for regenerative endodontics can all be developed with 3D printing.[39] For the regeneration of the pulp-dentin complex, porous scaffolds made possible by 3D printing technology can be filled with calcium hydroxide medication and calcium phosphate cement.[40]

PEDIATRIC SPACE MAINTAINERS

Utilizing 3D printing in crafting a space maintainer from a digital file offers a transformative solution. Space maintainers incorporating CAD-CAM or 3D print technology, utilizing modern and biocompatible materials, are termed 'Digital Space Maintainers.' This entire process, encompassing the patient's impression, casting, digitalization, design of the space maintainer (SM), and subsequent 3D printing, elevates the precision of the appliance to unprecedented levels, minimizing the potential for human error. The labor-intensive tasks involved in traditional methods, such as stabilizing the loop, soldering it at two points on the band, and subsequent polishing, are obviated, resulting in significant time savings chair-side.[41,42]

The 3D-printed appliance is produced as a single unit, reducing the likelihood of breakage and, consequently, diminishing the risk of appliance failure. In comparison to conventional appliances, a 3D-printed model exhibits a more intricate structure with a heightened level of detail

PEEK POLYMER

Polyetheretherketone (PEEK) materials exhibit a distinctive combination of robust mechanical properties, rigidity, opaqueness, and biocompatibility. The material offers chemical resistance, high-temperature stability, dimensional stability, and a broad range of processing possibilities. For patients with metal allergies or those averse to the metallic taste and weight, PEEK's natural tooth-colored appearance makes it a suitable choice. A 2015 study highlights several advantageous features of PEEK in orthodontics, positioning it as a promising option for aesthetically pleasing, metal-free orthodontic wires.[42]

In the context of space maintainers (SMs), PEEK enables the development of both the framework and prosthetic teeth within the same design module for removable, functional variations, resulting in a fully integrated design. This approach stands out in preference to others reliant on self-curing resin and artificial teeth.[42]

Ierardo et al. conducted a study on the utilization of PEEK polymer in the production of CAD-CAM Space Maintainers (SMs), where they crafted a lingual arch, a B&L, and a removable plate. Kun et al. assessed Digital B&L SMs made of PEEK polymer in children with unilateral loss of either the first or second molars, revealing that they were 75% lighter than conventional SMs. In a separate in vitro investigation, Guo et al. compared digitally produced RSMs crafted from PEEK polymer to traditional RSMs. The study demonstrated that digitally created RSMs exhibited a good fit on the model, indicating the suitability of the technique for clinical applications. This is in contrast to the conventional manufacturing approach, which involves numerous steps prone to errors during polymerization shrinkage of self-curing resin and necessitates grinding and polishing of the RSM, processes not required for digitally designed RSMs.[42]

BRUXZIR

BruxZir exhibits a remarkable three to five times greater fracture toughness compared to standard zirconia, boasting a flexural strength of up to 1,465 MPa. This exceptional toughness provides the material with excellent resistance to the masticatory forces encountered in the oral cavity. Due to its minimal thermal expansion, BruxZir remains stable in the mouth, maintaining its shape and avoiding any loosening in the teeth.[42]

The first documented instance of employing digital technology to create a Space Maintainer (SM) was presented by Soni. In the treatment of a 6-year-old female patient, BruxZir was chosen as the material for the device. The SM was strategically designed to receive support from both the canine and the primary second molar, enhancing retention, preventing tooth tipping, and ensuring even distribution of masticatory forces across the region of the extracted tooth.

Following a rigorous six-month testing period, no issues were reported with the appliance.[42]

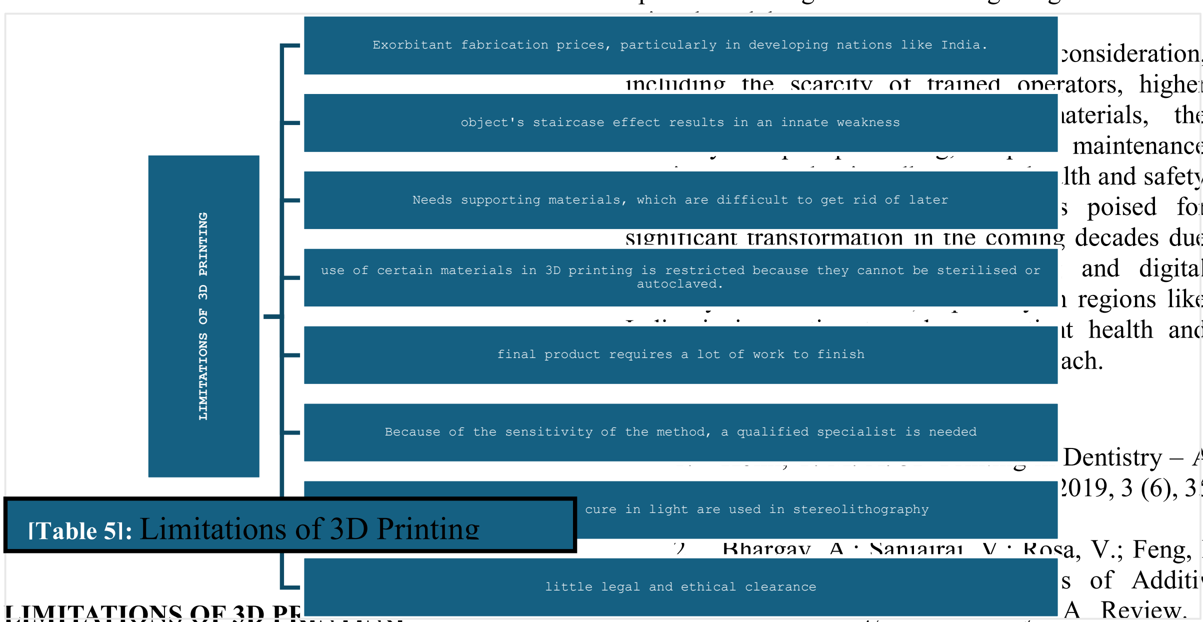
FUTURE PERSPECTIVE

4-D PRINTING THE FUTURE

4D printing, pioneered by Skylar Tibbitt and team, enables the creation of self-folding structures that respond to environmental cues. This technology transforms stable 3D printing materials into dynamic forms, allowing for materials that change shape over time or space. The programmable nature of 4D-printed materials opens up possibilities in restorative dentistry, potentially replacing traditional dental etching and bonding systems that rely on mechanical retention with a more chemically assisted approach.[43]

Future uses could involve:

1. 4D-printed dental restorative materials that can change from the centre to the edges in a predetermined amount of time, preventing fractures or marginal leaks.
2. It is feasible to design orthodontic appliances with a regulated, self-folding action that can angulate and move teeth in the desired directions. If this incredible technology is used, it has the potential to advance dentistry in a manner akin to that of CAD-CAM and 3D printing.[44]



[Table 5]: Limitations of 3D Printing

LIMITATIONS OF 3D PR

CLINICAL RELEVANCE

The integration of 3D printing into paediatric dentistry offers transformative benefits by enabling the fabrication of highly precise, customised appliances such as space maintainers, surgical guides, orthodontic splints, and prostheses. This technology enhances diagnostic capability, reduces chair-side time, and improves treatment outcomes, particularly in managing young, anxious, or special needs patients. By streamlining workflows through digital impressions and CAD-CAM systems, it allows clinicians to deliver minimally invasive, efficient, and patient-centred care. As 3D printing becomes more accessible, it is poised to become an essential tool in the delivery of high-quality paediatric dental services.

CONCLUSION

the utilization of 3D printing has empowered clinicians by providing more realistic training, enhancing conception, and improving surgical planning over the past decades. This transformative knowledge has significantly impacted dentistry, facilitating optimal precision with minimal clinical equipment and reduced chair-side time.

The integration of 3D printing, CAD-CAM, intra-oral scanning, and CBCT data has the potential to revolutionize dentistry. This technology enables the creation of intricate three-dimensional anatomical structures for research, treatment planning, training, and instructional purposes. Notably, it has contributed to achieving more accuracy, less invasiveness, and increased predictability in challenging craniofacial operations through the use of surgical guides and 3D ... consideration, including the scarcity of trained operators, higher ... aterials, the ... maintenance ... lth and safety ... s poised for significant transformation in the coming decades due ... and digital ... regions like ... it health and ... ach.

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