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Latest Approaches to Minimally Invasive Pediatric Dentistry: AI-Assisted Diagnostics Techniques, Behaviors Management, Preventive Interventions, Challenges and Limitations

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Abstract
Minimally invasive pediatric dentistry represents a new paradigm in managing children's oral health with disease prevention and early detection along with treatment that preserves the natural structure of teeth. Atraumatic restorative treatment, Hall crown technique, and cryosurgery are few techniques where comfort and psychological well-being for patients, particularly children with dental anxiety, have been kept as the most important objectives. Advanced technologies for better diagnostics and interventions include laser fluorescence, silver diamine fluoride, or 3D imaging in giving an exact diagnosis, hence less chances of invasive procedures. Behavior management has ensured a more optimistic and cooperative dental experience using the Tell-Show-Do method and virtual reality-based distraction. MIPD also incorporates caregiver involvement to reinforce oral health education and preventive practices at home. The new innovations will embody AI-assisted diagnostics and nanotechnology; thus, patients can expect to receive more targeted, more efficient treatments. Regenerative therapies will be capable of minimally invasive repair of tissues by restoration. Potential at MIPD is increasing despite challenges such as poor access to training, and access to advanced materials. The future directions include integrating emerging technologies, widening accessibility, and refining treatment protocols to improve the quality of life for pediatric patients. This paper examines the principles, techniques, innovations, and future trends in MIPD, highlighting its transformative role in pediatric dental care.
Keywords: Minimally Invasive Pediatric Dentistry; Atraumatic Restorative Treatment; Silver Diamine Fluoride; Hall Crown Technique; Behaviors Management; Laser Fluorescence; 3D Printing in Dentistry; AI-assisted Diagnostics; Early Orthodontic Interventions

1. Introduction

This is an approach in evolution, and it is designed to maintain health while retaining healthy tooth structure with diseases such as caries in effective management. This approach was founded based on the understanding that dental caries is an infectious disease that could be intercepted early enough, allowing the use of therapies that would minimize the amount of tissue loss and respect biological integrity (Showkat et al., 2020; Leal et al., 2022). One specific application of MID is significantly prominent in pediatric dentistry in a manner that addresses the exclusive needs of children, because children might be more apprehensive of dental anxiety and subsequent reactions to invasive procedures. Some common strategies in pediatric dentistry involved MID using some techniques and materials focused upon early detection and intervention, particularly on the utilization of silver diamine fluoride as an emerging minimally invasive practice in caries management. SDF not only arrests the progression of carious lesions but also promotes remineralization, which makes it a great treatment for children, especially those with special health care needs (Soni et al., 2021). Also, CAD/CAM systems have made it possible to provide restorations that are accurate, esthetic, and functional, which further enhances the minimally invasive approach (Reston et al., 2023).

The management of dental trauma in children also reflects the principles of MID. For instance, the restorative protocols for crown fractures in young patients can make use of minimally invasive techniques that are both conserving of tooth structure and give the best aesthetic outcomes (Reston et al., 2023). This is vital in pediatric dentistry where psychological effects of dental aesthetics may significantly affect a child's self-esteem and social

interaction (Gunda & Varma, 2013). More than that, the idea of minimum intervention dentistry that closely resembles MID emphasizes preventive philosophy, incorporating caries control into minimal operative intervention (Leal et al., 2022; Leme et al., 2022). It is very suitable in pediatric care where it targets education for the children and parents to have better oral hygiene and diet which may avoid the caries at first stage of their occurrence (Gunda & Varma, 2013). This helps pediatric dentists to reduce the number of more invasive treatments needed later.

2. Minimally Invasive Dentistry

It is a critical concept in pediatric dentistry, especially when it comes to children's oral health care. MID refers to the smallest change that a patient would notice in his or her treatment outcome, is relevant when considering interventions for children that cannot clearly verbalize what they experience and serves as a very important approach to assess the impact of oral health treatments on children's quality of life. This helps in clinical decision-making. This is because MID enables the measuring of the impact of dental treatments on the quality of life of children and their families. Researchers have demonstrated that ECC, for example, can highly influence the Oryol of children (Martins-Júnior et al., 2012). For instance, ECC is shown to affect negatively the Oryol of children, and this can also impact their parents, where oral health and family welfare go hand in hand with one another (Clementino et al., 2015). Using the MID, a practitioner can conclude if a treatment has led to a significant change in the quality of life of a child, not statistically (Ruff et al., 2016).

Further, patient-centered care is applied as per the MID in pediatric dentistry. Although children are entirely different from adult patients when considering their needs and responses, approaches that are often used in pediatric dentistry usually focus on the development stages and emotional response (Innes & Manton, 2017). For instance, the conservative interventions of MID like selective caries removal and preventive measures help in preserving tooth structure and pulp vitality important for long-term oral health of children (Igna et al., 2022; Alsaleh et al., 2020). A shift toward the minimally invasive approach results in healthier trajectories in children over time and better immediate outcomes of dental interventions. The role of caregivers in the oral health practices of children cannot be ignored. It has been observed that the knowledge and attitudes of caregivers have a great influence on the oral hygiene behaviors of children (Qiu et al., 2014). Through implementing MID in caregiver educational programs, they will be empowered to make decisions that can improve their children's oral health. It is significantly essential in populations requiring special health care needs and where applied preventive strategies significantly improve their oral health (Sireerat &Samnieng, 2018).

3. Principles of Minimally Invasive Dentistry in Pediatrics

A new paradigm for pediatric dentistry, coined Minimum Intervention Dentistry (MID), has concentrated its efforts on preventive care and early intervention with the management of dental caries. It aims to remove as little tooth structure as possible while performing just enough restorative interventions in an effort to minimize treatment burden on young patients while maximizing the amount of health that can be achieved.

3.1. Recognition

This principle suggests the identification of caries risk factors at an early stage, which can be carried out with a detailed assessment in terms of lifestyle analysis, saliva test, and diagnostic test on plaque. This concept helps recognize caries risk factors so that appropriate preventive strategy tailoring can be done (Innes & Manton, 2017; Walsh & Brostek, 2013). It is at the early stages that interventions can be introduced in order to prevent the disease progression of the carious lesions.

3.2. Reorientation

This principle emphasizes changing lifestyle factors that lead to dental caries. It educates patients and their families on the role of diet, oral hygiene practices, and regular dental visits. In this way, the dentist can influence lifestyle choices that minimize the risk of caries (Innes & Manton, 2017; Walsh & Brostek, 2013).

3.3. Remineralization

MID encourages topical agents, which include fluoride and casein phosphopeptides-amorphous calcium phosphates (CPP-ACP), in facilitating the remineralization of early carious lesions. It has been demonstrated that most carious lesions can be reversed when captured early enough, hence preventing more aggressive restorative interventions. Walsh & Brostek, 2013; Hefnawy, 2023, made this observation. The approach to remineralization resonates with the treatment philosophy of caries as a dynamic process rather than a static condition.

3.4. Repair

However, when the carious lesion penetrates to the point where the integrity is broken and cavitation appears, MID suggests conservative restorations that aim at taking care of the maximum preserved tooth structure. These treatments consist of selective carious tissue removal and the application of bioactive materials to contribute with self-curative processes of the remaining healthy tooth structure (Walsh & Brostek, 2013; Hefnawy, 2023). This

approach aims at doing damage control on the damaged dentition while preserving the amount of natural tooth structure feasible.

3.5. Review

The last principle is monitoring the child's oral health and progress of interventions. Regular follow up ensures that the care plan is adjusted periodically to ensure that the child has good oral health (Innes & Manton, 2017; Walsh & Brostek, 2013). This principle is indicative of a long-term commitment to maintaining oral health rather than something done once. Specifically, primary and mixed dentition management brings unique challenges to orthodontics that call for customized management. Some of the techniques that have turned out to be very effective have been the Mixed Dentition (MID) approaches of addressing the challenges as posed by developmental stages of dentition and related malocclusions.

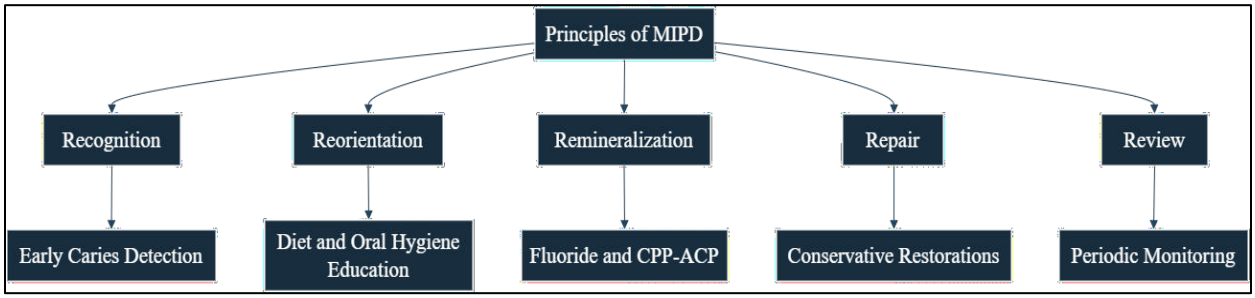

Figure 1. This figure demonstrates the five fundamental principles of MIPD recognition, reorientation, remineralization, repair, and review. Every principle is related to a particular application that includes the early detection of caries, education on oral hygiene, use of demineralizing agents like fluoride, conservative restorative approaches, and periodic follow-up to ensure long-term oral health.

It is difficult in the treatment of mixed dentition as malocclusion drastically affects dental and facial development of the child. Studies have indicated that early treatment in the mixed dentition is likely to result in a good success. Some examples include an 84-100% success in correcting crossbites in the mixed dentition using the Hexa Helix appliance (Yaseen & Acharya, 2012). These results improve aesthetics and functionality while reducing the propensity for being teased by the peers. Besides, the early treatments of orthodontics tend to be brief and nonsurgical, which is considerably significant for getting cooperation of young patients and their parents toward the treatment (Zhou et al., 2017). The Tanaka-Johnston and Moyers techniques of mixed dentition space analysis are unavoidable for correct diagnosis and designing of treatment since they help calculate the mesiodistal width of the teeth along with predicting the future occlusal disturbances (Abirami et al., 2022).

The techniques of MID not only target malocclusions but also timing and type of intervention. For instance, maxillary protraction therapy has been shown to be more effective if done in the primary dentition stage rather than at a later stage of treatment (Miao et al., 2021). This indicates that early intervention can result in marked skeletal improvement, which is especially advantageous for managing Class III malocclusions. It is further argued that the least invasive technique, such as 'M' spring for the midline diastema correction, has been under discussion as being efficient and saving treatment time, thus it should be done during the mixed dentition period (Suresh, 2023). It further enhances children, with unique anatomical and physiological characteristics, for the employment of MID techniques. Occlusal relationships of a child's primary dentition significantly predict the permanent dentitions, and therefore, correct assessments and interventions are warranted immediately if potential malocclusions are on the horizon (Jafarzadeh et al., 2021).

The association of anomalies both within and during the transition between primary to permanent dentition justifies thorough monitoring and intervention plans prior to the progression of developing anomalies into permanent dentition as undesirable malocclusions (Mukhopadhyay & Mitra, 2014). In addition to the characteristics of the malocclusion, the experience of the orthodontist can further determine the chosen treatment modalities. Indeed, most orthodontists begin the treatment when the dental age has reached late mixed or early permanent dentition stages, such as with Class II malocclusions, although successfully treatable at that stage, as for instance, illustrated by such studies as Chaparro et al. (2022). This highlights the particularity of a case-by-case treatment, depending on, among many factors, the child's age for developmental stages, with which the malocclusion will present.

4. Latest Minimally Invasive Techniques in Pediatric Dentistry

4.1. Caries Management

Recent progress in caries detection technology has greatly improved the ability of identifying dental caries in different stages, especially regarding early detection and assessment of non-cavitated lesions. The most prominent technology is laser fluorescence, digital radiography, and intraoral scanners equipped with advanced imaging techniques. One of the most common methods for the detection of dental caries is with laser fluorescence, which has been well known for proximal caries detection. DIAGNOdent uses a laser technology to stimulate the bacterial porphyrin fluorescence, which indicates the depth of demineralization. Several studies indicate that laser fluorescence has high sensitivity in the detection of carious lesions, in some cases even exceeding radiography's diagnostic capabilities. For instance, the diagnosis of early lesions is significantly facilitated by traditional bitewing radiography compared to laser fluorescence, among other things (Litzenburger et al., 2021; "Near-Infrared Transillumination Compared to Digital Bitewing Radiography for Proximal Caries Detection", 2023).

Another innovation is the integration of fluorescence technology in intraoral scanners, such as Trios 4 and 5, which can be useful in the distinction between carious and healthy structures within a tooth, thereby helping to enhance the diagnostic sensitivity (Lin, 2023; Schlenz et al., 2022).This modality remains a valuable tool in caries detection since it can radiographically depict carious lesions, but it has numerous disadvantages especially when used in the early detection of enamel lesions where the percentage needed to make such a detection is at least 30% demineralization (AbdELkader, 2024). In comparison of new technologies like NIRI or NI Imaging near infrared with traditional systems such as digital radiography, it showed that even both techniques would be able to see dentinal-penetration lesions; however, it showed that NIRI might prove sensitive enough to detect proximal early caries better than the other method ("Near-Infrared Transillumination Compared to Digital Bitewing Radiography for Proximal Caries Detection", 2023; Siew, 2024). This therefore points towards a complementary role for these technologies in that NIRI can complement traditional radiography.

Artificial intelligence is also advancing in caries detection; algorithms have reached an agreement of more than 90% in caries diagnosis from standardized images (Kühnisch et al., 2021). AI can analyze large data sets, which can improve the diagnostic accuracy and efficiency and may even reduce the variability associated with human examiners. Teledentistry applications using AI have shown much potential in early caries detection, especially in remote assessments (Abdat, 2024). Among non-invasive treatments, significant interest in pediatric dentistry has recently been in silver diamine fluoride (SDF) to arrest dental caries in children. SDF is an unpigmented solution of silver ions with fluoride that has been demonstrated to inhibit the advancement of existing lesions of dental caries and prevent their occurrence. The double effect makes SDF more important than other caries preventive agents in communities with less access to dental services and is therefore one important asset in managing dental caries in children ("Microtensile Bond Strength of Resin Modified Glass Ionomer Restoration in Carious Primary Molars Pretreated with Silver Diamine Fluoride", 2022; Zheng et al., 2022).

Several clinical studies have demonstrated the efficacy of SDF in arresting carious lesions in the primary teeth and the root surfaces of permanent teeth. A systematic review demonstrated that there was a considerable reduction in caries in preschool children with SDF treatment, suggesting its effectiveness as an economical intervention to control early childhood caries (Chu et al., 2011; Nuvvula & Mallineni, 2019). Moreover, SDF remineralization effects have been compared favorably with other treatments, such as sodium fluoride varnish, which means that SDF can obtain similar or better results in remineralizing early enamel caries (Gao et al., 2016; Soud et al., 2020). The mechanism behind effectiveness relates to the protective layer formed at the surface of the teeth to prevent bacterial growth and favors dentin remineralization for the affected dentin. Elasser et al. published it in the year 2022 like Firouzmandi et al. did in 2019.That is an important economic side aspect of SDF: non-invasive treatments such as that would delay more invasive restorations, which are a bit more expensive and will even require repeated visits to the dental clinic. Especially for high-risk populations that have a disproportionately high burden of dental caries compared to others (Schwendicke et al., 2014; Nuvvula & Mallineni, 2019). The help of SDF can allow dental practitioners to provide a relatively straightforward and practical intervention that reduces the need for multiple treatments, therefore diminishing health care costs (Schwendicke et al., 2014).

However, there are issues associated with SDF. Some of the problems include Treated teeth appear brown, which is aesthetically problematic for a few patients and their families. Still, at present, researchers are conducting studies to eradicate this possible problem by merging SDF with other agents like potassium iodide to evade the brown appearance while it is active against caries (Hussein et al., 2021).Further, the adoption of non-invasive treatments varies across patients because they may have had experience or may believe in other traditional methods of invasive nature (Chen et al., 2020; Srisomboon et al., 2022).

4.2. Restorative Techniques

Atraumatic restorative techniques (ART) are one of the least invasive forms of dental treatment and are very helpful in pediatric dentistry. It was first developed in the mid-1980s that was a response to the requirement for effective dental treatment of underprivileged populations. This focused on the preservation of tooth structure and to reduce patient discomfort and anxiety to the minimum. Sharma et al. (2021), Holmgren et al. (2013). The technique involves hand excavation of carious tissue followed by restoring the cavity with adhesive fluoride-releasing glass ionomer cement, thus inducing remineralization (Ahmad et al., 2022). Such a procedure is specifically excellent for children as it is very useful in avoiding anesthesia and pain from the traditional restorative treatment itself ("Atraumatic Restorative Treatment for Managing Dental Caries - A Review", 2020).

The ART procedure has been proven to make the patient much more compliant and less anxious when used in pediatric care. According to studies, almost 93% of children stated that they experienced no discomfort from the ART procedures, and a lot of them would readily come for similar treatments in future (Carvalho et al., 2009). Acceptance is essential for pediatrics because the pediatrician must handle not only the behavior but also anxiety in children. Use of nonpharmacological techniques of behavior management by a dentist, often alongside the ART, increases compliance of the child patients (Kateeb et al., 2013). Furthermore, parental acceptability of ART is also high, where the benefits of the procedure are well communicated; however, it is established that involving parents in treatment planning is important (Kateeb et al., 2013). Within the last decades, inclusion of silver diamine fluoride (SDF) within the ART protocol resulted in the development of a modified atraumatic restorative treatment technique with the term SMART. This approach addresses not only carious lesions but also improves the antibacterial properties of the treatment, which is very useful for children with multiple carious lesions or those who are hard to manage (Mohapatra, 2024; Hegde, 2024; Montecino, 2023).

The promising results of the preservation of tooth vitality and caries progression control have been shown through SDF application followed by GIC restoration (Mohapatra, 2024; Hegde, 2024). In a nutshell, ART and all its variants, including SMART, are a patient-friendly, effective, and economical approach for caries management in children. The technique is predicated on minimal intervention dentistry with its principles consisting of conservation of healthy tooth structure and preventive care approaches (Holmgren et al., 2013; Zanata et al., 2010). The more the world embraces the ART, then the more there will be insistence that this be part of pediatrics dental services especially in societies where more routine dental care access may not be easily made (Ahmad et al., 2022).

Table 1. Techniques and Their Applications in Minimally Invasive Pediatrics Dentistry.

Technique	Application	Advantages	In-text Citations
Atraumatic Restorative Treatment (ART)	Management of dental caries in primary teeth	No anesthesia, preserves structure, cost-effective	Arrow & Forrest, 2020; Holmgren et al., 2013
Hall Crown Technique	Sealing carious lesions	Preserves tooth structure, reduces aerosol exposure	Alsaleh et al., 2020; Nguyen et al., 2021
Cryosurgery	Treatment of oral lesions	Minimal discomfort, avoids local anesthesia	Rezende et al., 2014
Silver Diamine Fluoride (SDF)	Arresting caries progression	Non-invasive, remineralizes enamel, cost-effective	Gao et al., 2016; Schwendicke et al., 2014
CAD/CAM Systems	High-precision restorative treatments	Customization, enhanced aesthetics	Reston et al., 2023; Rech et al., 2022

GICs are a family of adhesive restorative materials with greatly improved outcomes for minimally invasive restorations. They possess a distinct combination of properties that are highly useful, such as chemical adhesion to tooth structures, release of fluoride, and biocompatibility, making these restorative materials even more effective at preserving the integrity of teeth while reducing the depth of cavity preparation. One of the main advantages of GICs is their chemical bonding to both enamel and dentin, which decreases microleakage and increases the longevity of restorations. This property is of special value in minimally invasive dentistry, where one seeks to preserve as much healthy tooth structure as possible while achieving effective restoration. GICs are also characterized by very low shrinkage stress when set that supports its application in minimum invasive approaches (Ngo & Vital, 2014; Yamada, 2018). Inclusion of resin-modified glass ionomer cements further improves the mechanical properties of such materials that has helped suit them to diverse clinical settings, especially to treat carious lesions which may penetrate deep into the teeth as well as for multi-surface restorations (Nujella et al., 2012; Singh et al., 2023).

Furthermore, the ability of the GICs to gradually release fluoride plays a prominent role in caries prevention and remineralization of other tooth structures adjacent to the sites. This characteristic of GICs not only aids in the management of carious lesions but also helps the tooth to be healthier as it prevents bacterial accumulation and favors remineralization (Khere et al., 2019; Mohamed et al., 2016). Studies have demonstrated the potential of GICs to easily facilitate remineralization of enamel and dentin, which is very useful in pediatric dental care as each preserved primary tooth is valuable in terms of growth and aesthetics (Amorim et al., 2011).Research has supported the clinical success of GICs, indicating that this restorative material can attain outcomes comparable to those established for amalgam in different dental applications (Amorim et al., 2011; Pires et al., 2018). For example, the atraumatic restorative treatment method that employs high-viscosity GICs has been effectively utilized for the management of caries in children, therefore becoming a proof of the material efficiency in the minimally invasive approach (Barbosa et al., 2016). Further, the development of giomers has combined the benefits of glass ionomers with the aesthetic properties of composite resins to provide a versatile option for clinicians (Hodisan et al., 2017; Usha & John, 2014).

4.3. Behavior Management

In minimally invasive pediatric dentistry, behavior management becomes crucial because it makes a positive dental experience for the children and reduces their anxiety by helping them to cooperate with the dental procedures. Among all these techniques of behavior management, BMTs are most important in pediatric dental care as the children will react to treatment in varied manners depending upon their age, previous experience, and temperament (Aldhelai, 2023; Shindova, 2020). One of the main purposes of behavior management is to reduce fear, which is one of the major challenges to successful treatment in children. Distraction, positive reinforcement, and the Tell-Show-Do method have been established as effective approaches for reducing anxiety and increasing cooperation in young patients (Alowi & Baghlaf, 2023; Riba et al., 2018; Pedrotti et al., 2015). For example, auditory distraction techniques have been used in pediatric dental patients to lower their anxiety levels, but often they are most effective in combination with other non-pharmacological interventions (Challa & Moses, 2022). Furthermore, studies reveal that informational techniques are better tolerated by parents than aversive methods, which is the importance of parental involvement and acceptance in selecting behavior management strategies (Aldhelai, 2023; Pedrotti et al., 2015).

Table 2. Behavior Management Strategies in MIPD.

Technique	Description	Application Example	In-text Citations
Tell-Show-Do	Gradual exposure to procedures	Explaining steps to reduce anxiety	Alowi & Baghlaf, 2023
Virtual Reality (VR)	Immersive distraction	Reducing fear during procedures like venipuncture	Wong et al., 2020
Positive Reinforcement	Rewarding cooperative behavior	Verbal praise or small gifts post-procedure	Riba et al., 2018
Music Therapy	Soothing auditory environment	Reduces anxiety during dental treatments	Agliati et al., 2018
Animal-assisted Therapy	Interaction with therapy animals	Reduces fear and emotional stress	López-Fernández, 2023

Behavior management techniques applied are not only good for the child but are also important for the dentist. Pediatric dentists must therefore have a library of BMTs to be in apposition with the needs as presented by anxious or resisting children. As cited by Slaven et al., 2019; Kawia et al., 2015, majority pediatric dentists feel that there is inadequate preparation with these approaches. This underlines that more comprehensive training and educational requirements on behavior management through dental curricula are highly recommended for future practitioners in the complexities associated with pediatric care (Zalan, 2022). It would not be wise to ignore parental acceptance in the management of behaviors. The perception of parents concerning different techniques of behavior management has been highly found to influence their willingness to have their children undergo dental procedures (Aldhelai, 2023; Pedrotti et al., 2015). The relationship, therefore, highlights the importance of proper communication with the parents about the benefits and appropriateness of the chosen BMTs to elicit a collaborative approach toward pediatric dental care.

5. Orthodontic and Preventive Interventions

Early orthodontic interventions on children have been taken with minimally invasive approaches as they can potentially improve outcomes in treatment, reduce the level of discomfort, and the period before recovery. The methods are well applicable during the mixed dentition stage where early interventions would play a significant role in influencing dental and skeletal development. One of them is piezocision, which involves the induction of

microincisions in the buccal gingiva and promoting fast movement of teeth through decortication of alveolar bone. This enhances the rate of alveolar bone turnover that leads to anabolic and catabolic activities that allow for rapid movements during orthodontics (Hou et al., 2019). Piezocision is one of the minimally invasive methods that can be followed by grafting in case it is required. Thus, it is pretty flexible to be applied by orthodontic practitioners (Hou et al., 2019). Besides, a comparative study has revealed that piezocision can be combined with other more conservative methods such as laser-assisted flapless corticotomy to make the tooth movement even faster (Alfawal et al., 2018). Micro-osteoperforations is yet another novel technique where controlled small holes are created on the alveolar bone. This provokes localized bone remodeling, thus improving the mobility of teeth and shortening the time of treatment in general (Sinha, 2024).

MOPs have also been shown to minimize patient compliance as the results can be obtained sooner and with lesser discomfort than in the case of traditional methods (Sinha, 2024). The benefit of MOPs is that they are non-invasive, and orthodontists and patients prefer it over more invasive surgical interventions (Onyeaso, 2024). Interceptive orthodontics is also an important component of early intervention. This treatment can prevent the establishment of more complex orthodontic conditions. Such severe anteroposterior crossbites, ectopic molars, and discrepancies in arch length are well-treated if the intervention is made timely (Sandhu, 2024; Inchingolo et al., 2022). Studies have proven that early intervention is more effective as studies have revealed that children treated early have a better prognosis than those treated late (Sandhu, 2024). Besides, latest advances in 3D printing technology have allowed developing computer-assisted guides for surgical interventions. This makes the minimally invasive orthodontic procedures more accurate and efficient (Hou et al., 2019). All these technological breakthroughs increase not only the accuracy of interventions but also comfort and satisfaction of a patient.

6. Role of Technology and Innovation

Digital technologies revolutionize minimal invasive pediatric dentistry, especially with the introduction of intraoral scanners and 3D printing. This will make the patient feel more comfortable and improve diagnostics along with treatment, leading to a better clinical result when dealing with young patients.Intraoral scanners became an important tool for dentists working with pediatric patients, replacing traditional methods like impression techniques that are normally uncomfy and anxiety-evoking for children. IOS enables the capture of extremely accurate digital impressions, without impression materials like alginate or polyvinyl siloxane, which are quite offensive to young patients (Bellapukonda, 2024; Saini, 2024). Digital impressions captured using IOS are established to be similar in their accuracy to conventional impressions, but with a significantly improved efficiency and comfort in the workflow and for the patient (Ting-shu& Sun, 2014; Alkadi, 2023; Panwar et al., 2023). The quick acquisition of digital models makes possible the immediate preparation of treatment and increases communication among dental practitioners and patients, and the overall experience becomes less terrifying for children (Sfondrini et al., 2018; Mangano et al., 2017).

Thirdly, 3D printing is modifying the treatment alternatives in pediatric dentistry. This technology enables the fabrication of patient-specific dental appliances, including orthodontic devices and surgical guides, tailored to the unique anatomical needs of pediatric patients (Tyagi, 2024). The rapid production of these appliances minimizes the time children spend in treatment and reduces the number of appointments required, which is very helpful for young patients who cannot tolerate long dental visits (Khurshid, 2023). Patient-specific models are also possible for production through 3D printing, which is applied for pre-surgical planning and increased accuracy of interventions with less invasiveness of procedures (Rotaru, 2023).

Table 3. Technologies in Minimally Invasive pediatric Dentistry.

Technology	Functionality	Benefits	In-text Citations
Laser Fluorescence	Detects early caries	High sensitivity, non-invasive	Litzenburger et al., 2021
AI-assisted Diagnostics	Image analysis, caries detection	Improved accuracy, remote access	Kühnisch et al., 2021
3D Printing	Customized dental appliances	Patient-specific, fewer visits	Tyagi, 2024; Khurshid, 2023
Digital Radiography	Imaging for caries detection	High-resolution imaging, reduced radiation	Siew, 2024; Lin, 2023
Intraoral Scanners	Digital impressions	Accurate, reduces anxiety from traditional molds	Sfondrini et al., 2018

Digital technologies also influence educational aspects in pediatric dentistry. These advanced tools that dentist professionals will use will give them the opportunity to introduce the new generation of the patients on how to carry

out oral hygiene using diagrams and interactivity in the demo models (Bellapukonda, 2024; Poduval, 2021). This introduction shall form a foundation for healthy perspectives of proper oral hygiene during early childhood, which shall finally manifest in better health conditions after several years (Khurshid, 2023). As the mainstreaming of AI continues, especially with the treatment of children through minimally invasive interventions, the final aim is optimizing decision-making processes as a way of improving patient outcomes and tailored treatments. All these are done through the application of AI in various healthcare ways ranging from surgical planning, patient monitoring, to post-operative care.

Develop Clinical Decision Support Systems, using algorithms from the field of machine learning. These algorithms are supposed to further aid the clinical information analyzing and processing abilities. For instance, through these decisions, while at work, healthcare providers shall be accorded insight, in the real time, into what applies concerning patients plus evidence-based clinical guidelines established at any time (Olorunsogo, 2024; Ramírez, 2024). For instance, with minimal invasive surgeries, AI may be utilized in the preoperative planning phase to forecast complications and then adapt the surgical techniques based on a specific patient's anatomy (Kuemmerli et al., 2023). The predictability in children is crucial because the anatomical variations will highly influence the surgical results.AI technologies also hold promise in enhancing the precision of minimally invasive procedures. For example, the integration of AI with imaging technologies enhances the ability to identify and interpret images, a very important feature in advising surgeons on operating procedures (Kuemmerli et al., 2023). This is true, particularly in pediatric surgery, where the margins for errors are almost negligible and accuracy matters. The minimally invasive procedures have been demonstrated by numerous studies to be associated with improved recovery and short hospital stays in comparison to traditional surgeries, and AI-based approaches can further optimize these outcomes (Tan et al., 2021).

Another major importance of AI is that in postoperative care and rehabilitation, the patient can be constantly monitored. Continuous monitoring by health professionals with AI can track how recovery is happening and can thus diagnose complications early, with the provision for timely intervention (Mennella et al., 2023). Pediatric patients do not always report their discomfort or complications, so this can be important. Additionally, AI can assist in tailoring rehabilitation protocols to the needs of each child, which makes recovery efficient and effective (Mennella et al., 2023). There cannot be omitted ethical considerations regarding the AI within the decision-making framework for health-related matters, especially concerning children. However, AI could be integrated for a more favorable decision-making process and evokes concerns related to algorithm-based transparency and biases involved in the recommendations themselves (Biller-Andorno et al., 2021;, Rolfes et al., 2023). Clinicians, as well as the involved families, may question uncertainty when their dependency upon such AI systems exists, regarding the medical recommendations and reliability of these. Accordingly, the AI should be designed by taking into consideration human values and ethics that ensure openness and accountability of their prescriptions (Olorunsogo, 2024).

7. Benefits of Minimally Invasive Dentistry in Pediatrics

The management of treatment-related anxiety and fear in the pediatric patient is a highly significant component of pediatric healthcare. Different interventions have been reviewed for their ability to alleviate the emotional responses, and the level of evidence supporting the effect of non-pharmacologic interventions is substantial. There is a prominent method used; it is therapeutic play, along with play therapy that significantly reduces the level of anxiety in hospitalized children. For example, a study by Zengin et al. proved that the therapeutic play did not only reduce anxiety and fear levels in children after liver transplantation but also had positive impacts on parental anxiety levels, suggesting that such interventions have a more general benefit (Zengin et al., 2021). Other studies have also supported the use of therapeutic play in pediatric oncology environments where this was shown to reduce anxiety and pain during procedures such as catheterization (Zengin et al., 2021).

Another novel application in pediatric care is virtual reality-based interventions, which are recently on the rise. Wong et al. documented the advantages of VR in pain and anxiety relief in children with cancer during procedures such as venipuncture (Wong et al., 2020). This is supported by the systematic review, which established the efficacy of VR in reducing anxiety during a range of medical procedures, including wound care for burn patients (Shiferaw et al., 2022). The immersive nature of VR seems to distract the patient from his or her immediate fears and discomfort, thereby offering a more positive treatment experience. Music therapy is another non-invasive approach that has been promising in reducing anxiety in medical procedures. Agliati et al. performed an integrative review that demonstrated music's ability to greatly reduce anxiety and fear in dental care, indicating that auditory stimuli can be used to create a soothing environment for pediatric patients (Agliati et al., 2018). This is especially relevant in environments where children may be fearful of the sounds involved in medical treatments.

Other research have also been conducted on the use of mobile applications that educate and prepare children for medical procedures to reduce preoperative anxiety. Wantanakorn et al. showed that mobile applications could be

used to reduce anxiety levels in pediatric patients undergoing bone marrow aspirations, emphasizing the need for age-appropriate educational tools in anxiety management (Wantanakorn et al., 2018). The findings further suggest that necessary information regarding applications can be accessible and engaging for children, thus reducing fear associated with aspects of medical procedures that are unknown. Apart from these, animal-assisted therapy, as a helpful approach, has been designed in pediatric care. According to research by López-Fernández, interaction with therapy animals was able to diminish pain, fear, and anxiety of hospitalized children to an appreciable extent, and, therefore, it may help decrease emotional stress and comfort when medical procedures are stressful (López-Fernández, 2023).

8. Challenges and Limitations

Limitations associated with minimally invasive approaches to dentistry, especially those associated with advanced caries or more complex cases, are critical in understanding their effective clinical applications. The limitations can be considered in terms of challenges arising around clinical practice, knowledge deficiency of the professionals, and technical limitations inherently associated with the techniques.

8.1. Limitation

The dentist has preference and knowledge about the minimal invasive approach. A study suggested that most dentists tend to remove caries completely, probably because they are not aware of the minimally invasive techniques like stepwise excavation or chemo mechanical caries removal (CMCR) (Alnahwi et al., 2018). This tendency results in the underutilization of the minimally invasive approaches, even though they can save the tooth structure and minimize the patient's discomfort (Reddy et al., 2015). However, lack of training in the application of such techniques has been experienced, resulting in fewer practices in the clinics (Alnahwi et al., 2018; Almahdy et al., 2017). One of the gaps education and training can fill is in knowledge about the effectiveness and application of minimally invasive dentistry (Showkat et al., 2020).

Technical challenges from the application of minimally invasive techniques limit these efforts. Methods like laser ablation and CMCR are particularly designed to remove the carious tissue while preserving the healthy dentin; however, how efficient such methods are can significantly depend on the severity of carious lesions and the nature of the tooth involved (García-Contreras et al., 2014; Raveendran et al., 2020). For example, in deep caries, remaining dentin often has poor microhardness and may also be contaminated by bacteria; thus, results from these treatments can be hard to achieve (Anwar et al., 2017; Villat et al., 2016). Patientspecific factors like the risk for their caries and also the adherence of the patient to preventive practices plays a key role in ensuring the success of these treatments (Desai et al., 2021; Giacaman et al., 2018). This variability demands a more personalized treatment approach, which may involve time and, at specific times, is not actually feasible in real practice. Moreover, dependence on some materials and methodologies may also create problems. For example, agents like chemomechanical agents, Papacarie, and Carisolv promise in the selective removal of caries with variable efficacies for different types of soft tissues of decay (Reddy et al., 2015; García-Contreras et al., 2014). Minimally invasive treatments often depend on the availability of good materials and skilled professionals while applying them that is a great variation between practice settings (Pozos-Guillén et al., 2021).

9. Case Studies and Success Stories

Minimally invasive techniques have been adopted with a great degree of acceptance in pediatric dentistry due to their efficacy in maintaining tooth structure along with the necessary treatment of dental caries and other oral diseases. All of these, namely ART, HCT, and cryosurgery, are excellent examples, with unique clinical applications for each one. Among all these minimally invasive procedures applied clinically by removing decay without using a local anesthetic by employing hand instruments, one should mention Atraumatic Restorative Treatment, or briefly ART. This technique, indeed, has well shown and proven to be highly efficacious in enhancing the quality of children's oral health life and thereby reduced the referral of patients toward specialists for the management of young patients' caries cases. Arrow & Forrest (2020). ART is ideal for treating cavities in primary teeth because it allows for effective restoration with minimal discomfort and anxiety in children (Gomes et al., 2022). The technique has been validated in most of the clinical trials, which confirm its success and acceptance by children and their parents (Arrow & Forrest, 2020; Arrow et al., 2020). It is also an inexpensive method and thus practicable for the poor, who comprise children, among others, particularly in most places where children have been found to find it hard to access dental care services (Gomes et al., 2022).

9.1. Hall Crown Technique

Hall Crown Technique is another minimally invasive technique, caries sealing with a stainless-steel crown, without any preparation or removal of caries from the tooth. This also follows the guidelines of the International Caries Classification and Management System (ICCMS) and was deemed effective for the management of carious lesions with the preservation of the tooth structure (Nguyen et al., 2021). It has been more useful for community dental

settings wherein it is observed that this approach seriously reduces the requirement for a more invasive procedure (Nguyen et al., 2021). The technique is also especially relevant nowadays in terms of the COVID-19 pandemic, wherein infection control becomes of the utmost essence. For this purpose, the technique can also reduce aerosol generation in treatment (Alsaleh et al., 2020).

Cryosurgery is another one of the latest minimally invasive techniques adopted to effectively manage the oral lesion of children. This procedure is well-tolerated by a child without any requirement of local anesthesia. Hence, this is good for those fearful patients (Rezende et al., 2014). Multiple lesions can be simultaneously treated. With the lowest complication ratio, this enhances the appeal to the pediatric practice (Rezende et al., 2014).

Furthermore, the use of advanced technologies in restorative protocols, such as CAD/CAM systems, has made it easier to execute minimally invasive techniques. These technologies allow for high-precision restorations with minimal preparation of the natural dental tissue (Reston et al., 2023; RECH et al., 2022). The use of biomimetic and adhesive restorative materials has also been changed to address caries at the microscopic level, which is a mainstay of minimally invasive dentistry (Showkat et al., 2020).

10. Future Directions and Research Priorities

Nanotechnology and regenerative therapies are at the threshold of revolutionizing pediatric dental care, through innovation in the prevention, diagnosis, and treatment of dental conditions. The integration of these technologies can make the treatments more effective with reduced invasiveness, and is especially useful in pediatric patients, who are easily frightened during dental procedures. At one time referred to as nano dentistry, nanotechnology remains a concept of the last few years which utilizes material of nanoscale and also tools of such dimension to gain improved results in dentistry. By taking an example, application in the field of restorative dentistry, of nanomaterial resulted in discovery of biomimetic which seems identical in texture in order to offer characteristics nearer than one natural way (Chokkattu et al., 2023). These materials can also be engineered to have specific properties such as enhanced biocompatibility and controlled drug release, which are important for effective treatment in children (Polini et al., 2013; Agrawal, 2023). Nanotechnology also enables the building of nanoscale drug delivery systems targeted to specific sites in the oral cavity, thus allowing a more targeted treatment of dental caries and periodontal disease (Dave, 2023; Neel et al., 2015).

Regenerative therapies with emphasis on stem cell are very promising for the management of most pediatric dental conditions like congenital anomalies and trauma to the teeth. The plasticity of dental stem cells allows them to differentiate into many types of cells that are needed for tissue reconstruction, which could be one of the least invasive treatments other than the conventional treatments (Aldomyati, 2023; Tatullo et al., 2020). For example, using regenerative techniques, loss or destruction of dental tissue can be replaced and hence is less likely to require more invasive forms of surgical treatment (Zimța et al., 2019). Furthermore, tissue engineering and bioactive materials are more likely to enhance the regeneration of periodontal tissues hence becoming a more viable remedy for conditions that involve the supportive structures of the teeth (Gallo et al., 2022; Larsson et al., 2015). Furthermore, the combination of nanotechnology and regenerative therapies often results in synergistic effects that enhance treatment outcomes. In this regard, silver nanoparticles mixed with fluoride varnishes have been discovered to promote the remineralization of primary teeth, which thereby prevents early signs of dental caries among children (Girón et al., 2017). This heals existing dental conditions and prevents future decay.

Conclusion

Minimally invasive pediatric dentistry has emerged as one of the cornerstones of contemporary treatment, providing an interface in which effective treatment does not compromise the preservation of any natural structures and the psychological comfort. Techniques such as ART, Hall crown technique, and cryosurgery have managed dental caries and lesions with minimal discomfort and highly acceptable among patients. The use of technologies in the form of laser fluorescence and AI-assisted diagnostics has enhanced the diagnostic accuracy and treatment planning as well as 3D printing with its customized and efficient intervention in orthodontic treatment. Maturity has ensured that behavior management is still a core element where the comfort and cooperation with treatment are ensured in the case of pediatric patients. In fact, positive reinforcement with distractions using virtual reality has remarkably reduced anxiety levels, enabling treatment outcomes to be improved from their general levels. Even prevention by the caregivers will promote further long-term benefits by MIPD. The limitations of MIPD, including resource constraints and variability in practitioner expertise, call for further education and research. New fields, such as nanotechnology and regenerative therapies, hold immense promise for advancing MIPD by providing minimally invasive solutions for tissue repair and caries prevention. As the science progresses, the inclusion of latest technologies with patient-centered care will establish MIPD's place in revolutionizing pediatric dental health. MIPD ensures a comprehensive care that focuses on both the clinical and psychosocial aspects, hence giving it a strong basis for a lifelong oral health.

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Author contributions
All Co-authors were participated in data collection, manuscript editing, reviewing, table and figure creating. The original manuscript draft was creating by first author, and cross ponding was supervisor the manuscript and all authors given the final approval for manuscript submission to journal for publication.

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