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REVIEW

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# Technology-enhanced chairside and remote compliance management techniques in paediatric dentistry and early orthodontic treatment

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## Abstract

Poor cooperation, dental anxiety, and phobia frequently hinder treatment in children and adolescents, jeopardizing both immediate outcomes and long-term oral health. Such challenges highlight the critical importance of behavioural and compliance management and have consequently driven a shift towards technology-enhanced strategies for improving chairside and remote compliance management. Through a comprehensive literature search, all studies published after January 2015 on chairside and remote compliance management in pediatric dentistry and early orthodontic treatment were included. Virtual reality (VR) for distraction and desensitization, laser therapy for pain reduction, cognitive behavioural therapy (CBT) and advanced anesthetic delivery systems and other emerging behavioural management technologies are all innovations in traditional chairside compliance management techniques. Furthermore, the growth of early orthodontic treatment has established remote compliance monitoring as a critical research frontier in pediatric dentistry. Remote compliance management using teledentistry platforms, wearable devices, Internet of things (IoT) based applications, and artificial intelligence (AI) assisted tools has proven effective for monitoring compliance of children and adolescents undergoing early orthodontic treatment beyond clinical settings. This review concludes that emerging technologies are fundamentally reshaping behavioural management in pediatric dentistry. Their synergistic integration is constructing a comprehensive management ecosystem, fostering a proactive and patient-centred paradigm that enhances both therapeutic efficacy and patient experience. Future progress in this field hinges on addressing challenges related to cost-effectiveness, data integration and privacy, the development of minimally invasive techniques, and the establishment of standardized objective assessment metrics. The continuous evolution and integration of these digital tools hold immense potential to optimize overall treatment outcomes in pediatric oral healthcare.

## Keywords

Behaviour management; Compliance management; Remote monitoring; Paediatric dentistry; Early orthodontic treatment

## 1. Introduction

Oral diseases, including caries, dental trauma, and malocclusion, significantly impact both physical and psychological health in children and adolescents, leading to substantial reductions in quality of life [1–8]. Consequently, early prevention and timely intervention for these conditions are essential to protect the comprehensive health of children and adolescents. However, during the developmental stages of childhood and adolescence, compliance with dental treatment often presents significant challenges, which are likely attributable to substantial cognitive and behavioural shifts. Research has identified various factors influencing compliance, including perceived comfort, treatment options, parental attitudes, and patient personality [9]. Among these, dental fear is a leading contributor to inadequate compliance [10], may prompt paediatric patients to entirely evade dental treatment, and increase procedural risk [11], especially among patients with special healthcare needs (such as autism spectrum disorder, intellectual disabilities, or anxiety disorders) [12]. Given that good compliance is a critical determinant of achieving optimal treatment outcomes, addressing these challenges necessitates that dental professionals implement long-term, rigorous compliance management strategies to ensure effective oral treatments for children and adolescents [13].

Traditional behavioural management techniques, including


  

non-pharmacological and pharmacological approaches, aim to promote the provision of quality care. However, the variable efficacy, dependency on practitioner skills, and limited scope for personalization, which are the critical limitations of these traditional behavioural management techniques, have spurred the exploration of innovative solutions. In recent years, based on traditional behavioural management techniques and principles (such as distraction, communication, tell-show-do, *etc.*), a variety of novel and effective techniques have emerged, such as immersive virtual reality (VR) experience, laser therapy, and cognitive behaviour therapy (CBT), which can effectively alleviate dental anxiety and fear in children and adolescents during dental treatment. Concurrently, with the occurrence of the COVID-19 pandemic and the growing demand for early orthodontic treatment, particular interest has been spurred among paediatric dentists and orthodontists in achieving remote monitoring of treatment progress. As a result, research on compliance management employing some emerging technologies, such as teledentistry, artificial intelligence (AI)-assisted remote monitoring systems, and sensor-based applications, is rapidly evolving. These innovative compliance management techniques provide new opportunities to enhance patient engagement and improve treatment outcomes. Therefore, to provide better dental treatments, dentists need to possess a comprehensive understanding of the various emerging compliance management techniques. This narrative review summarizes the recent progress and prospects of chairside and remote compliance management methods in paediatric dentistry and early orthodontic treatment (Fig. 1), while exploring the potential challenges and future directions of these advanced techniques. Therefore, this paper provides a valuable clinical reference for paediatric dentists to understand the frontier methods of behavioural management for children and adolescents and to improve dental treatment outcomes.

## 2. Methodology

This narrative review uses a systematic approach to review the relevant literature published between 2015 and 2025. Electronic databases including PubMed, Scopus, Web of Science, and Cochrane Library were searched using the keywords "(((TS = (pediatric OR child*)) AND TS = (orthodontic OR dental OR dentistry)) AND TS = (behavio*)) AND TS = (manag* OR guid*)". Inclusion criteria included clinical trials, randomized controlled trials, systematic reviews, and observational studies, focusing on behavioural management or remote compliance monitoring in patients under 18 years old. Studies that are not published in the English language or whose full text cannot be obtained are excluded. All the retrieved studies were manually screened.

## 3. Research progress of chairside compliance management in paediatric dentistry

Chairside compliance management is the most common modality of behaviour management, broadly categorized into non-pharmacological and pharmacological approaches. Non-pharmacological techniques, favored for their cost-effectiveness and minimal risk, focus on establishing clear communication and building rapport with paediatric patients to alleviate dental fear and anxiety [14, 15]. Examples include communication, Tell-Show-Do (TSD), reinforcement, parental presence/absence (PPA), modelling, distraction, voice control, desensitization, and others. On the contrary, pharmacological behaviour management controls pain and anxiety through the employment of analgesics or sedatives. This section focuses primarily on recent technological advancements that have provided dental practitioners with

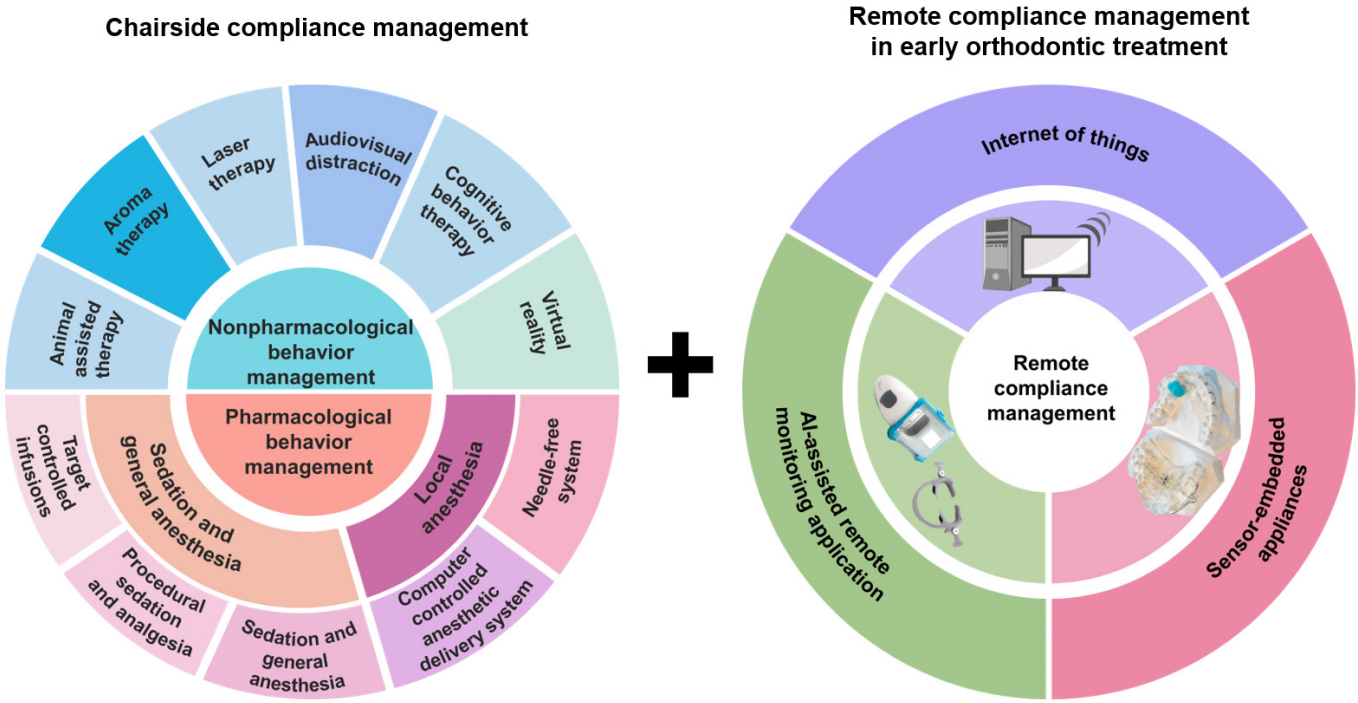


**FIGURE 1. Graphic presentation of the issues discussed in the manuscript.** AI: artificial intelligence.

innovative chairside behaviour management options.

## 3.1 Nonpharmacological behaviour management techniques

### 3.1.1 Distraction

Distraction is an effective and widely implemented behaviour management strategy. It operates on the theory that pain perception is contingent on attention to the noxious stimulus. Therefore, redirecting attention from the stimulus can significantly reduce or even eliminate pain perception [16]. While basic audiovisual distraction is well-established [17, 18], research has explored novel technologies in paediatric dental behaviour management based on distraction theory. The active audiovisual distraction requires patients to actively participate in distraction techniques to reduce pain perception better. Recent research demonstrates that wireless-joystick video games on chair-mounted portable tablets significantly outperform traditional audiovisual distractions in reducing pediatric dental fear and pain during treatment [19]. With the continuous advancement of technology, based on traditional distraction technology, emerging behavioural management technologies have emerged in large numbers.

### 3.1.2 Virtual reality (VR)

Recent scholarly investigations have explored the potential of VR to alleviate dental fear and anxiety in children and adolescents [20–22]. VR combines audio, visual, and kinesthetic inputs to enhance immersion, effectively diverting children's attention from the clinical environment and reducing their pain and anxiety (Fig. 2, Ref. [22–24]). Research indicates that higher immersion levels correlate with greater pain relief [25]. Compared with traditional behaviour management techniques, such as audiovisual distraction and Tell-Show-Do (TSD), VR offers significant advantages in alleviating anxiety and reducing pain perception in paediatric patients [26–28]. Furthermore, traditional behaviour management techniques can be challenging to implement and may prove ineffective for children with mental disorders. In such cases, VR presents a promising alternative. Evidence demonstrates that VR significantly mitigates dental anxiety during treatment for children with mild intellectual disabilities, effectively managing anxiety levels that might otherwise impede dental care [29]. Additionally, adopting VR as a distraction technique is reported to markedly decrease anxiety and improve dental treatment behaviour in children with autism spectrum disorder [30].

Moreover, virtual reality exposure therapy (VRET) has emerged as a derivative technology of VR. As a form of desensitization, VRET simulates operational processes, instruments, and clinical environments, thereby familiarizing patients with the entire procedure before treatment. This pre-operative familiarization could reduce the sense of the unknown and consequently alleviate dental fear and anxiety before dental procedures [31, 32]. Evidence suggests that VRET could significantly diminish preoperative anxiety and enhance compliance during paediatric anesthesia induction through simulating treatment processes [33].

Although current research has confirmed the effectiveness of VR as an emerging behavioural management technology, the high cost of VR equipment greatly limits its application. Therefore, more research is needed in the future to compare the cost-benefit analysis of VR as a behavioural management technology.

### 3.1.3 Laser therapy

In recent years, laser therapy has emerged as a promising adjunct to paediatric dentistry, offering innovative non-pharmacological approaches for pain management and behaviour modification with clinical integration potential [34–36]. Laser therapy works by modulating pain signals, effectively elevating pain thresholds and reducing reliance on anesthetic agents, as supported by studies confirming its analgesic effects [37, 38]. Studies have confirmed the effectiveness of laser therapy in reducing local anesthesia injection pain and improving patient compliance among paediatric patients, and emphasized its potential as a pre-anesthesia behavioural management technique [39, 40]. Consistent findings suggest laser therapy may also serve as a promising strategy for managing paediatric dental fear and anxiety. At present, there are relatively few studies on laser therapy for behavioural management techniques. The effectiveness of such techniques in the behavioural management of paediatric patients needs to be further evaluated, as well as their integration with standard clinical protocols and their application in diverse dental procedures.

### 3.1.4 Other methods

#### 3.1.4.1 Aromatherapy

Aromatherapy is primarily administered via inhalation. Evidence confirms that inhaled aromatic compounds effectively reduce dental anxiety, culminating in relaxation and sedation [41]. Recent research demonstrates lavender and patchouli essential oils significantly diminish paediatric dental fear and anxiety, with lavender aroma functioning by activating the parasympathetic nervous system [42]. Owing to its non-invasive nature and the encouraging outcomes observed, aromatherapy emerges as a promising adjunct in the behavioural management of paediatric dentistry. Further research is advisable to determine optimal essential oil concentrations to maximize therapeutic outcomes while minimizing adverse effects in paediatric dental care [43].

#### 3.1.4.2 Animal-assisted therapy (AAT)

AAT involves professionally trained animals to promote patient cooperation and ameliorate behaviours that impede treatment efficacy. In paediatric dentistry, dog-assisted therapy (DAT) is the main form of AAT and has proven effective in reducing dental fear and pain among children and adolescents [44, 45]. A recent randomized controlled trial confirmed AAT's capacity to alleviate pain perception and dental anxiety in children receiving local anesthesia [46]. Moreover, DAT has been shown to outperform traditional non-pharmacological methods in managing dental fears and enhancing patient compliance [47]. Despite these benefits, the implementation of AAT raises parents' concerns regarding zoonotic infections and animal behaviour risks. Therefore, all potential risk factors associated with therapeutic animals and trainers should be eliminated to ensure safety before AAT is applied.

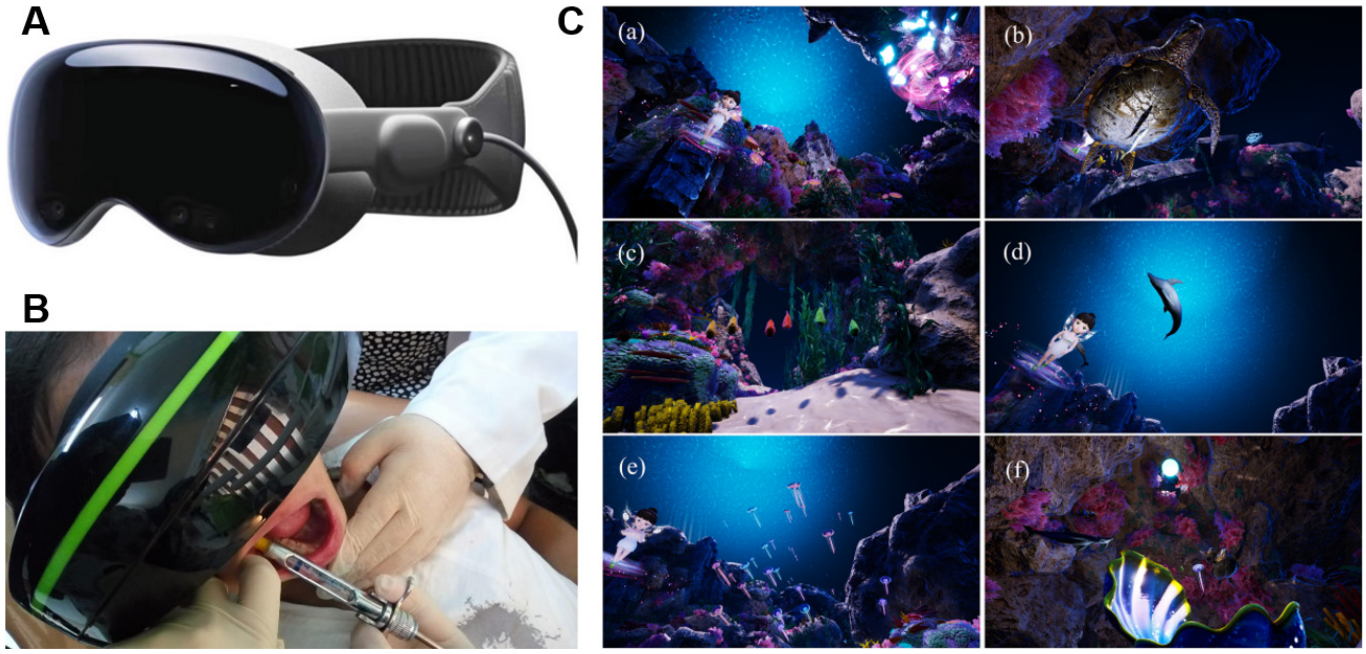


**FIGURE 2. The application of VR to alleviate dental anxiety of children.** (A) The Apple Vision Pro headset (From Waisberg *et al.* [23], 2024, licensed under CC BY 4.0.). (B) Local anesthesia administration with immersive virtual reality (Reproduced from Alshatrat *et al.* [22], 2022, with permission from the John Wiley & Sons, Inc.). (C) Screenshot of custom scenario. (a–f) show the storyline of a virtual story scenario. (From Ran *et al.* [24], 2021, licensed under CC BY 4.0.).

#### 3.1.4.3 Hypnotherapy

Hypnotherapy can induce the desired alterations in patients' sensations, perceptions, feelings, thoughts, and behavior [48]. Girón *et al.* [49] demonstrated its superiority over conventional behaviour management techniques in reducing paediatric dental anxiety and pain. The findings indicated that hypnotized patients exhibited significantly lower heart rates and skin conductance, along with enhanced anxiety and pain self-regulation capacities. Although studies demonstrate clear benefits of hypnotherapy on child behaviour management, high-quality evidence to firmly establish its efficacy is still lacking [50, 51]. Notably, hypnotherapy is not a one-size-fits-all solution, and its effectiveness can vary based on individual suggestibility, practitioner expertise, and clinical context. Therefore, further exploration of hypnotherapy in paediatric dental care is imperative, requiring improved understanding among dental professionals along with targeted training programs and specialized staff deployment [52].

#### 3.1.4.4 Cognitive behaviour therapy (CBT)

Compared with the above-mentioned individual behaviour management methods, the CBT derived from the integration of multiple behaviour management technologies shows potential application prospects in chairside behaviour management for children and adolescents. CBT integrates behavioural management approaches, including audiovisual distraction, positive reinforcement, behavioural modeling, hypnosis, breathing relaxation, medical games, and positive self-talk. As first-line psychotherapy in paediatric care, CBT effectively addresses various behavioural and mental health conditions such as post-traumatic stress disorder (PTSD), substance abuse, and eating disorders [53, 54]. Expanding its application to dentistry, CBT focuses on alleviating treatment-related anxiety and fear by empowering patients to recognize their oral health anxieties and develop coping strategies for modifying negative cognitive-behavioural responses during dental procedures [55]. Shahnavaz *et al.* [56] found that CBT significantly improved children's negative attitudes toward dental treatment, with 73% showing reduced fearful behaviours versus 13% in the conventional group. Furthermore, at 1-year follow-up, 91% of CBT-treated children no longer displayed dental phobia, compared with 25% in the conventional group [57]. These findings underscore CBT's efficacy as a behavioural management technique in alleviating dental phobia in children with long-term sustained benefits.

However, despite CBT's proven effectiveness, its dental application has been constrained by limited access to clinical psychologists, treatment procedure complexities, and venue restrictions [58]. To address these barriers, researchers have recently developed Internet-based CBT (ICBT), utilizing online resources for more feasible CBT interventions. Evidence indicates that 91% of patients reported reduced dental worry and improved anxiety management following self-help ICBT [59]. A randomized controlled trial by Schibbye *et al.* [60] further demonstrated that 41% of participants no longer met criteria for dental or injection fears after ICBT intervention. These findings highlighted ICBT's potential as an effective and accessible intervention for managing dental and injection fear.

In summary, by equipping patients and parents with coping strategies, CBT offers a personalized approach to managing dental fear and anxiety, consistent with the evolving development of the patient-centered care paradigm. It not only alleviates distress during dental visits, but also cultivates long-term psychological resilience, thereby driving lasting positive

shifts in their attitudes towards dental treatment. However, the requirements of CBT for professionals greatly limit its application in clinical practice, and the integration of CBT behavioural management technology will require pediatric dentists to have higher professional skills. Although ICBT can effectively reduce this demand and lower the application threshold of CBT, ICBT is still an unattainable tool for many regions with underdeveloped or unreliable Internet. Thus, in the future, more research is needed to explore how to integrate CBT into behavioural management technology efficiently and easily, to reduce the demand for professionals and increase the popularity of its application.

In general, the field of non-pharmacological behaviour management techniques is undergoing a profound transformation driven by technological innovation. Advanced tools such as VR, laser therapy, and CBT have shown the potential to surpass traditional behavioural management techniques in alleviating anxiety, controlling pain, and improving compliance, especially for children with special needs. However, the current research shows a significant imbalance. The efficacy of VR is supported by more randomized controlled trials, but the paradox between its high cost and popularity has not been resolved. The long-term benefits of CBT (including ICBT) are clear, but its dependence on professional resources or the digital divide limits its widespread implementation. Although the preliminary results of laser therapy, aromatherapy, animal-assisted therapy, and hypnotherapy are encouraging, most of them lack large-scale and high-quality research to establish their standardized application schemes and definitive evidence levels. This reveals that the general gap between the advancement of technology and clinical accessibility and the solidity of evidence still exists. The key to future development requires that the research paradigm shift from validating individual techniques to comparative effectiveness research and implementation science, thereby truly realizing the transformation of these emerging technologies from literature to clinical practice.

## 3.2 Pharmacological behaviour management techniques

### 3.2.1 Local anesthesia

Pharmacological behaviour management techniques focus on pain control, predominantly achieved through local anesthesia [61]. The local anesthesia functions by blocking pain conduction in peripheral nerves through the injection of anesthetic agents adjacent to neural pathways. The primary fear of local anesthesia in children and adolescents derives from the pain perception associated with needle injection. To alleviate the pain of traditional needle injection, researchers have developed innovative local anesthesia injection techniques, such as computer-controlled anesthetic delivery system (CCLAD) and needle-free system.

#### 3.2.1.1 Computer controlled anaesthetic delivery system (CCLAD)

Computer Controlled Anaesthetic Delivery System (CCLAD) is a novel technique that enables the computer to automatically and precisely control the injection speed, pressure, and volume, which shows promise for reducing pain and improving cooperation during local anesthesia in children (Fig. 3, Ref. [62, 63]) [63, 64]. A study demonstrated that CCLAD markedly relieves injection pain and suggested its potential to alleviate associated dental fear and anxiety [62]. However, other research found no significant difference between CCLAD and conventional techniques regarding pain perception, anxiety, and behavior [65, 66]. These varying results may be attributed to the different methodologies used to measure outcomes, such as objective or subjective methods to assess children's physiological changes in pain or anxiety. Therefore, further research is needed to validate the effectiveness of CCLAD in controlling pain during local anesthesia in children and adolescents.

#### 3.2.1.2 Needle-free system

Eliminating needles, the principal trigger of dental phobia and uncooperative behaviour in children and adolescents, needle-free injection systems primarily utilize pressurized gas to deliver anesthetic medication into tissue for local anesthesia (Fig. 4A, Ref. [67–69]). By avoiding needle puncture, needle-free systems potentially reduce the pain experienced compared with traditional injections, offering a promising alternative for pain control and behaviour management in paediatric dentistry (Fig. 4B,C). Studies have demonstrated the effectiveness of needle-free systems in reducing pain and dental anxiety during local infiltration anesthesia or pre-anesthesia. Kaya *et al*. [67] found that needle-free systems for infiltration anesthesia generated less pain than traditional puncture anesthesia and were preferred by children. Belevcikli *et al*. [70] reported that while pain perception might not be significantly different from needle injections, the needle-free injection system can effectively reduce children's anxiety and improve behaviour management.

Although needle-free injection systems are recommended for use in paediatric dentistry because they can significantly reduce pain in children during infiltration anesthesia, it has been found that children prefer traditional injection methods to needle-free injection systems during anesthesia [67, 70]. The reason may be that the noise and pressure generated by the needle-free system have a negative impact on children's pain perception and anesthesia method preference [61, 71, 72]. In addition, the needle-free system quickly injects the anesthetic solution into the tissue through a high-pressure gas to achieve the anesthetic effect, and this may pose some potential risks. As shown in Fig. 4D, the penetration depth of anesthetic solution is controlled by adjusting the supply pressure, thus affecting the anesthetic effect [73]. Correspondingly, the higher supply pressure increases the risk of adverse events, such as lacerations. Furthermore, research suggests that injection techniques play a role. Compared with perpendicular injection, oblique injection is more conducive to the dispersion of anesthetic drugs in the tissue, which can reduce lacerations and puncture wounds [68]. In short, the needle-free injection system has great potential to alleviate the anxiety and fear of children and adolescents by eliminating the needle injection and has a positive impact on behaviour management. However, more research is needed in the future to focus on mitigating the side effects of needle-free injection systems, such as noise, pressure, and lacerations.

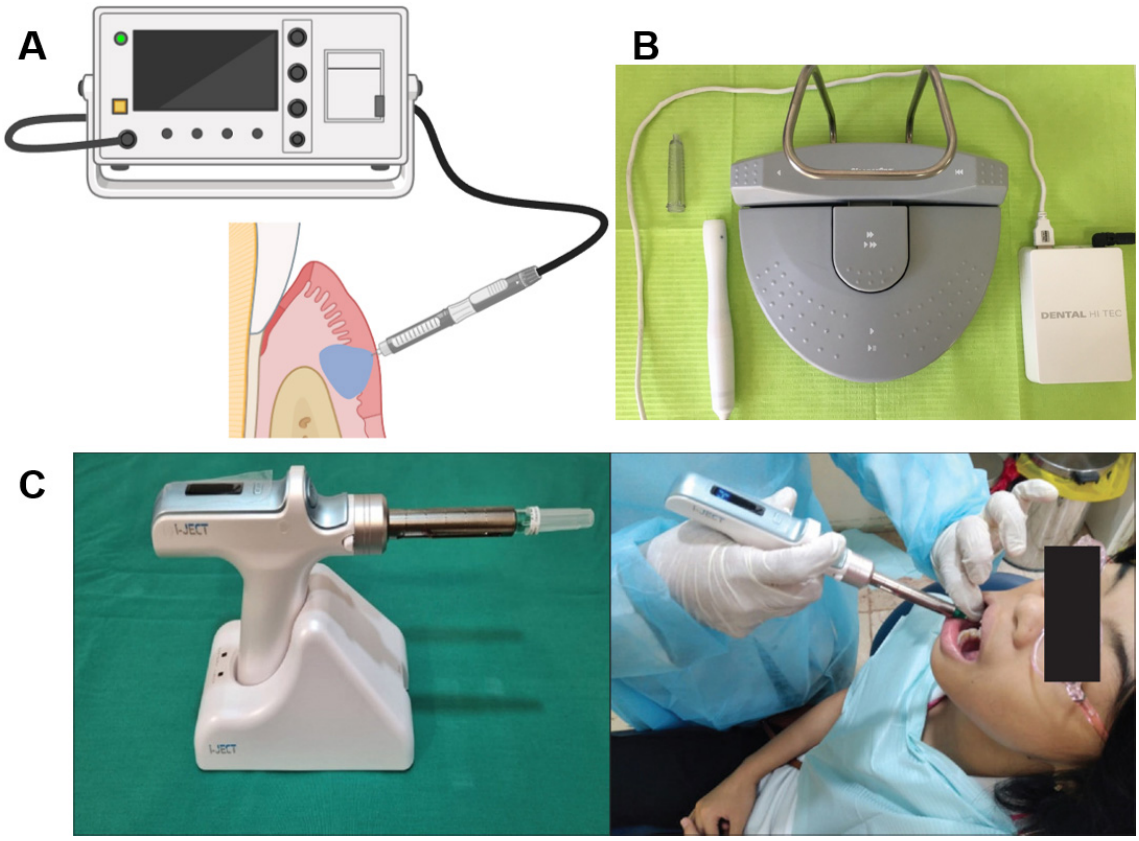


**FIGURE 3. The demonstration of CCLAD and its application for local infiltration anesthesia for children.** (A) The demonstration of CCLAD. (B) SleeperOne® device (From Vitale *et al.* [62], 2023, licensed under CC BY 4.0.). (C) Administering LA using I-JECT system (From Beegum *et al.* [63], 2024, licensed under CC BY 4.0.).

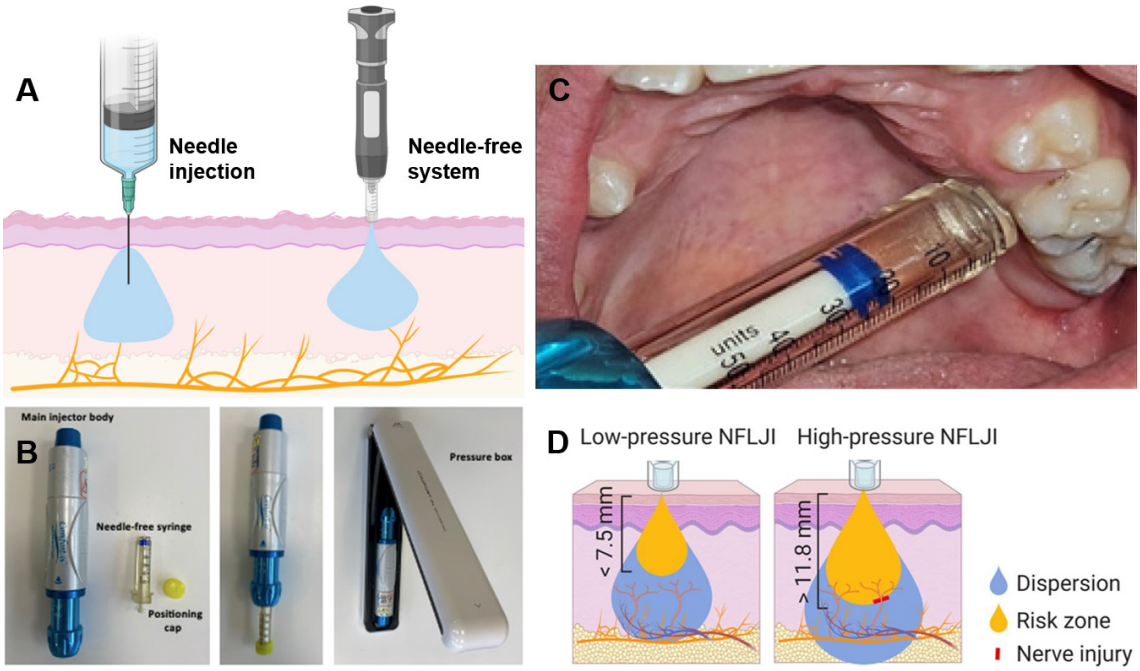


**FIGURE 4. Demonstration of needle-free system and its application for local infiltration anesthesia for children.** (A) Demonstration of the needle-free system and needle injection. (B) Comfort-in™ injection system (Reproduced from Kaya *et al.* [67], 2023, with permission from the John Wiley & Sons, Inc.). (C) Application of needle-free system for local anesthesia (From Altan *et al.* [69], 2025, licensed under CC BY 4.0.). (D) Penetration depth of anesthetic solution under different supply pressure (From Gao *et al.* [68], 2021, licensed under CC BY 4.0.). NFLJI: needle-free liquid jet injection.

### 3.2.2 Sedation and general anesthesia

For extremely uncooperative children and adolescents, pharmacological sedation and general anesthesia represent the ultimate behavioural management strategies. Sedation employs medication to induce a state of reduced consciousness while maintaining protective and involuntary reflexes, whereas general anesthesia eliminates conscious perception of pain and subdues general reflexes.

Given the high cost, potential risks, and specialist requirements of general anesthesia, many parents prefer sedation techniques [74]. Current primary sedation methods involve inhalation and oral sedatives. Inhalation sedation, which bypasses liver metabolism, is favored for its efficient and reliable sedative effects. Among these, nitrous oxide inhalation sedation is most frequently utilized. A recent study indicated that integrating nitrous oxide sedation in behaviour management techniques can facilitate comprehensive dental treatment for anxious or semi-cooperative children, thereby reducing the necessity for general anesthesia [75]. Other agents include intranasal midazolam and dexmedetomidine. A recent randomized controlled clinical trial concluded that intranasal midazolam and nitrous oxide were equally effective in sedative outcomes, physiological parameters, and adverse effects, whereas dexmedetomidine showed inferior efficacy [76].

However, for children with extreme anxiety and uncooperativeness, effective management often requires analgesia in addition to sedation. This need has driven increased attention toward procedural sedation and analgesia (PSA) in recent years. PSA, formerly known as conscious sedation, is a minimally invasive technique that strategically applies one or more pharmaceutical preparations to provide both sedation and analgesia while meticulously maintaining physiological functions such as spontaneous breathing, airway reflex, and hemodynamic stability [77]. It offers advantages such as multiple administration routes, effective sedative and analgesic outcomes, and mild postoperative adverse reactions. Studies have explored optimal drug combinations to achieve better effects in inducing sedation and analgesia. Nie *et al*. [78] summarized that combining oral midazolam with intranasal dexmedetomidine surpasses oral midazolam alone in sedative effect and treatment compliance. Rational combinations can lower required doses while boosting the efficacy. Agarwal *et al*. [79] compared four analgesic-sedative drug combinations for paediatric dental pulp therapy, revealing varying sedative and analgesic effects, as well as behavioural management during and after surgery.

Nasal and oral administration are currently the primary routes employed in PSA. However, nasal administration can cause burning sensations, irritation, and tearing, which pose challenges to paediatric behaviour management [80]. Buccal transmucosal administration shows a promising non-invasive alternative in paediatric dentistry, attributed to its rapid drug absorption and enhanced bioavailability resulting from bypassing hepatic metabolism [81]. However, the unpleasant taste of many drugs currently limits the application scope of buccal transmucosal administration [82]. The progress of medicine has facilitated the rise of target-controlled infusions (TCI), a computerized intravenous infusion system based on pharmacokinetics. It allows anesthesiologists to determine the required target drug concentration and computerized infusion rates according to pharmacokinetic parameters, thereby maintaining the desired concentration and controlling anesthesia depths to meet clinical anesthesia requirements [83]. Recent developments have expanded TCI into a "closed-loop system" that uses feedback to tailor sedation depth requirements to specific surgical needs [84]. However, pharmacokinetic models vary among adults and children of different ages. Therefore, more research is needed to develop paediatric TCI models and evaluate their practical applicability in the future [85].

In conclusion, although extensive studies have investigated the employment of different sedative and analgesic drugs, as well as the effects of various administration routes on managing behaviour in extremely incoordinated children, the optimal drug combination and administration route are still unidentified. Therefore, future research should further explore the synthesis of novel sedative and analgesic drugs and their administration routes, and examine their role in paediatric behaviour management.

## 4. Research progress of remote compliance management in early orthodontic treatment

The dynamic growth and development of the jaws present a unique therapeutic window for orthodontics. In children and adolescents, severe malocclusions, including mandibular retrusion, maxillary protrusion, and other skeletal discrepancies, can be effectively managed or even completely corrected through timely interceptive orthodontic treatment [86]. This significant advantage is an important reason why early orthodontic intervention is receiving growing attention from orthodontists and parents. Using removable appliances (such as functional appliances or clear aligners) and fixed appliances to correct malocclusions in children and adolescents is currently the main approach in early orthodontic treatment. Removable appliances require higher patient compliance because patients can freely remove them. Most removable appliances require patients to wear them regularly at home to complete early orthodontic treatment. The required wear time varies among different orthodontic appliances due to differences in their working mechanisms. For example, functional appliances generally need to be worn by patients for 10–12 hours a day, while clear aligners usually need to be worn for 20–22 hours a day. However, the treatment effectiveness is closely related to the wear time of the appliance [87–89]. Insufficient cooperation, such as inadequate wear time, can significantly compromise treatment outcomes. Lack of cooperation, such as insufficient wearing time, failure to replace clear aligners on schedule, and inadequate oral hygiene maintenance, may compromise treatment efficacy, extend the treatment duration, and increase the risk of complications, including root resorption, caries, and gingival inflammation, among others [90–92]. Thus, the ideal orthodontic outcomes depend not only on continuous innovation in orthodontic technology, but also on patients' good compliance in wearing appliances, especially

for paediatric patients [93, 94]. A systematic review has shown that continuous remote monitoring can enhance patient cooperation [95]. However, at present, the remote monitoring technique for patients undergoing early orthodontic treatment is mainly food-grade dyes soluble in saliva which is embedded on the surface of the clear aligners. Then, the orthodontist subjectively assesses the patient's compliance at home based on the color change of the dye [96]. But these remote monitoring techniques are too rough to objectively and accurately judge the patient's compliance. Consequently, various software and applications have recently emerged to offer objective and long-term remote monitoring of orthodontic patient compliance.

Teledentistry utilizes remote communication platforms, including mobile phones, computers, the Internet, and other electronic communication devices, to transmit the patients' dental health data to dentists. This enables continuous evaluation of treatment plans and remote monitoring of treatment outcomes and compliance [97, 98]. With the integration of AI, teledentistry has been significantly advanced, facilitating the early diagnosis of various oral conditions and revolutionizing remote compliance management. The COVID-19 pandemic further acted as a catalyst, accelerating the adoption and exploration of teledentistry solutions. According to recent bibliometric analyses, research on teledentistry has experienced significant growth following the COVID-19 pandemic [99, 100]. These emerging technologies, mainly including AI-assisted applications, sensors-embedded appliances, and IoT-based systems, are reshaping compliance management in early orthodontic treatment. However, integrating them into clinical practice requires a critical understanding of their respective advantages, limitations, and the evidence supporting their use.

## 4.1 AI-assisted remote monitoring application

A novel orthodontic application called dental monitoring (DM) has emerged in this field, which integrates AI with teledentistry to achieve accurate, semi-automated monitoring of orthodontic patients. DM mainly comprises external devices, smartphones, and AI systems (Fig. 5A, Ref. [101–103]). It can capture 2D intraoral photos using a professional device or smartphone, upload them for 3D processing by the AI system to accurately calculate tooth movement, and remind patients to wear their aligners (Fig. 5B,C) [101]. The literature shows that DM-based monitoring can significantly reduce the number of appointments without affecting the treatment duration or outcome [104]. It has been found that patients with DM for remote monitoring experienced an average reduction of 1.7 months in the first phase of treatment, which demonstrates a more efficient tooth movement, thereby reducing the treatment duration [105]. Furthermore, the remote communication and monitoring capabilities of DM can enhance orthodontic patients' motivation to participate in their treatment, thereby improving their compliance [106]. In addition to remotely monitoring appliance wear and assessing tooth movement, DM can also remotely detect patients' oral hygiene, periodontal conditions, caries, orthodontic emergencies (such as archwire disengagement, bracket detachment, and occlusal interferences), and retainer stability. For instance, Sangalli *et al.* [102] utilized the DM app to monitor the oral hygiene of orthodontic patients during the COVID-19 pandemic, finding it effective in improving plaque control and reducing caries incidence in these patients.

The primary strength of AI-assisted monitoring lies in its ability to provide semi-automated, objective supervision across multiple aspects of treatment, such as orthodontic progress, oral hygiene, and emergency detection. This facilitates a more proactive, data-driven approach to case management. However, its feasibility is limited by high costs, technical requirements for image capture, and varying levels of patient acceptance. For example, a study noted that around 15% of participants are dissatisfied with DM and prefer traditional office visits [104]. This means that technological advancement is not generally equivalent to improvements in patient experience.

In addition, although early evidence is encouraging, there is a notable lack of large-scale, long-term randomized controlled trials to verify its clinical and cost-effectiveness across different populations. Data security and privacy remain key concerns, as the system handles sensitive patient images and health information. From a clinical perspective, these platforms are best suited for practices with adequate technical infrastructure and patients or families willing to actively participate, which may lead to disparities in access.

## 4.2 Sensor-embedded appliances for compliance monitoring

Advances in medical wearable devices have offered convenient and reliable ways for remote patient monitoring, covering health status, treatment progress, and compliance. Over the last decade, the employment of wearable devices in the orofacial region has gradually increased. When equipped with sensors, these devices can continuously collect real-time, objective patient data, thus providing opportunities to formulate precise and personalized treatment strategies [96]. Currently, assessing treatment progress is the primary way to gauge patients' compliance. However, doctors' subjective views of patients can seriously undermine the accuracy. Therefore, there is a need for objective and reliable modalities to monitor compliance remotely. Although the accuracy of medical wearable devices is still controversial, they hold great promise in continuous home health monitoring, strengthening patient compliance, and improving treatment outcomes [107].

In recent years, microelectronic sensors embedded in orthodontic appliances have been successfully employed to monitor patients' compliance (Fig. 6, Ref. [108–111]) [108, 112–114]. Most are temperature-sensitive and can detect the wear time of removable appliances by sensing the difference between intraoral and ambient temperature [96]. Studies have found that micro-sensors installed inside removable appliances can objectively and remotely monitor patients' compliance, allowing for a more reliable assessment of the therapeutic effect of the removable appliances [110, 115, 116]. Although some studies have reported opposite conclusions, most studies believe that when aware of being monitored for compliance by microelectronic sensors, most patients tend to demonstrate better compliance in wearing removable appliances [89].

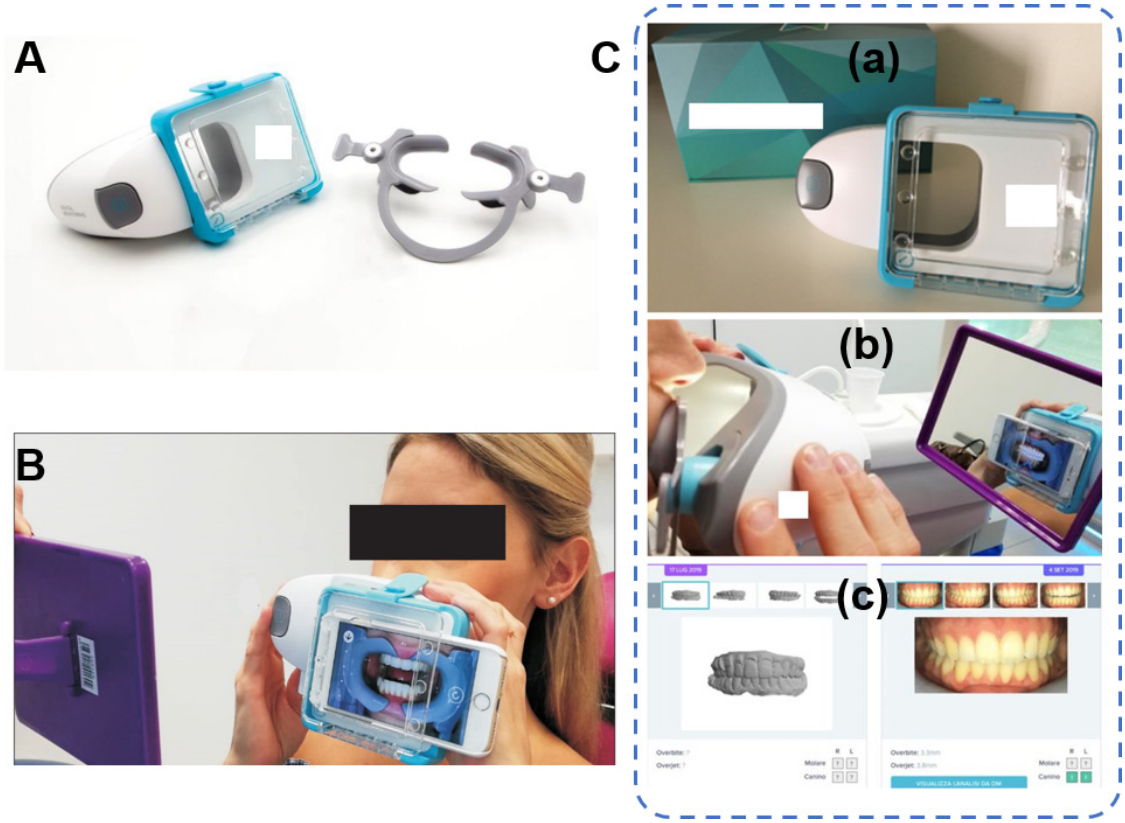


**FIGURE 5. Display and software interface of DM.** (A) Dental monitoring® (DM) ScanBox© and cheek retractor (From Caruso *et al.* [101], 2021, licensed under CC BY 4.0.). (B) ScanBox© for remote monitoring by Dental Monitoring® (From Sangalli *et al.* [103], 2022, licensed under CC BY 4.0.). (C) Scanbox© for remote 2D photo monitoring by Dental Monitoring® (a), device used by the patient (b), and software interface (c) (From Sangalli *et al.* [102], 2021, licensed under CC BY 4.0.).

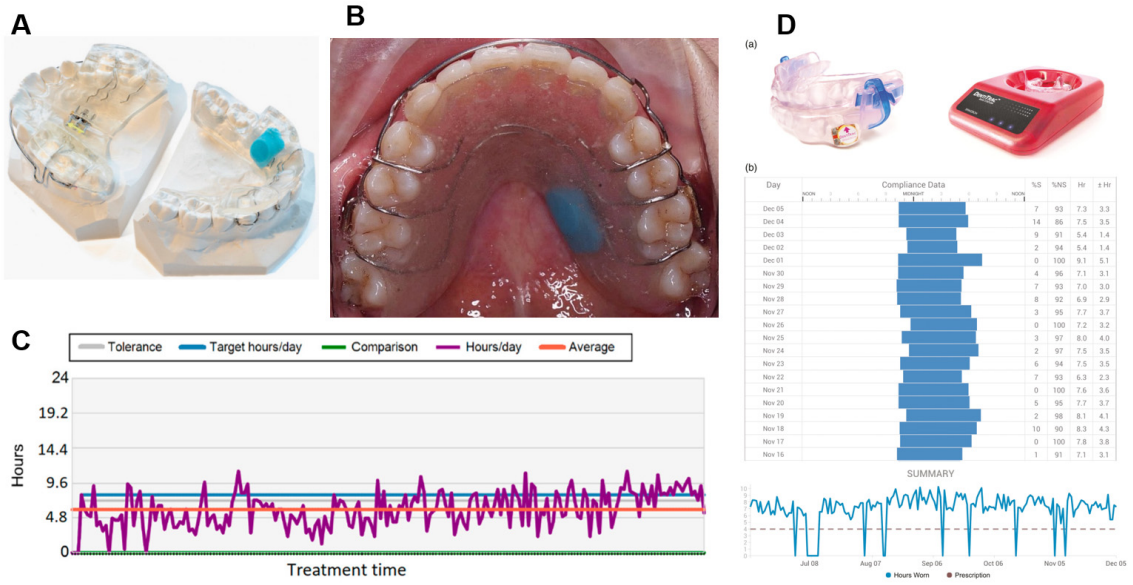


**FIGURE 6. Sensors are employed to remotely monitor the compliance for early orthodontic treatment.** (A) Twin Block appliance with the TheraMon® microsensor in the mandibular lingual section (From Frilund *et al.* [108], 2023, licensed under CC BY 4.0.). (B) Microsensor embedded in upper removable Hawley retainer (From Khaled *et al.* [109], 2023, licensed under CC BY 4.0.). (C) Demonstration of employing the software to convert sensor data into the wearing time of the appliance (From Nahajowski *et al.* [110], 2022, licensed under CC BY 4.0.). (D) (a) The DentiTrac® sensor embedded in the lower appliance (Left). The DentiTrac® base station (Right). (b) Example readout from the Braebon® Cloud Service, showing nightly wear duration over 200 days (From Chen *et al.* [111], 2025, licensed under CC BY 4.0.).

The principal strength of sensor-based monitoring lies in its objectivity and reliability in measuring actual intraoral wear time. Studies show that the awareness of being monitored itself can improve compliance, and this psychological effect is beneficial for behavior improvement. However, technical limitations include the impact of sensor placement on accuracy, finite battery life, and increased cost and bulk to the appliance [117, 118]. Although evidence is steadily increasing, it still mainly comes from small-scale or observational studies; high-quality randomized controlled trials comparing sensor-driven outcomes with traditional monitoring results are limited. Clinically, sensor-embedded appliances are a powerful tool for clinical research and for managing poorly compliant patients in whom objective data is crucial. However, routine use requires consideration of cost-effectiveness as well as the practical feasibility of data acquisition and interpretation.

### 4.3 Internet of things (IoT)-based compliance monitoring

The evolution of remote monitoring extends beyond individual devices to interconnected systems. The IoT connects computing devices, machines, and objects via the internet to form systems that deliver intelligent services to end users [119], thereby enabling remote compliance monitoring for children and adolescents. Numerous studies have shown that IoT can remotely monitor compliance with appliance wear, particularly for removable appliances, effectively reducing follow-up visits and improving treatment outcomes [120]. Currently, mobile apps are commonly used for remote compliance monitoring. Systematic reviews confirmed the effectiveness of mobile apps in improving short-term oral hygiene by reducing dental plaque and gingival bleeding in patients with fixed appliances [121, 122]. In addition, social media has also shown promise in enhancing wear compliance in adolescents with removable retainers, thereby improving treatment outcomes [123].

IoT interventions, especially mobile health applications, offer advantages such as scalability, relatively low cost, and ease of integration into daily life. Their strength lies in leveraging widely used technology (smartphones) to encourage engagement and foster positive habits. Systematic reviews support their short-term effectiveness in improving oral hygiene in orthodontic patients. However, evidence regarding their long-term impact on actual appliance wear time and ultimate treatment outcomes is limited and sometimes even contradictory [124]. A major limitation of IoT applications in remotely monitoring for orthodontic patients is the digital divide, unequal access to smartphones or reliable internet may exacerbate health disparities. In addition, most studies focus on behavioral outcomes, such as plaque control, rather than direct orthodontic effects. At the same time, data privacy remains an unresolved challenge in this connected ecosystem. In clinical practice, IoT is suitable as an auxiliary support technique within a broader compliance strategy, particularly for health maintenance and reminder functions, but it cannot replace objective measurements of wearing time for appliance.

The field of remote compliance monitoring is transitioning from proving technical feasibility to addressing complex implementation challenges. When compared, AI-assisted platforms offer the most comprehensive clinical oversight, but at the highest cost and complexity. Sensor-embedded appliances provide the gold standard for objective wear-time data, but are limited to that single parameter and face hardware constraints. IoT-based systems are the most accessible and scalable for behavioral support, but lack the objective measurement capabilities and robust evidence for direct orthodontic outcome improvement.

A critical limitation across all technologies is the lack of high-level evidence. Many studies are pilot projects, case series, or short-term evaluations without control groups. There is an urgent need for large-scale, longitudinal randomized controlled trials that not only validate efficacy, but also assess long-term cost-effectiveness, data security protocols, and equitable access. Additionally, research demonstrating that improved remote compliance monitoring can translate into better final orthodontic treatment outcomes, shorter treatment times, and higher patient satisfaction remains insufficient.

In short, these emerging technologies are paving a new paradigm for early orthodontic compliance management, shifting it from a passive, clinic-centered model to an active, continuous, patient-engaged process. Their successful integration into mainstream practice depends not only on technological advancement, but also on the establishment of comparative effectiveness studies, standardized data protection frameworks, and strategies to ensure that these tools enhance, rather than exacerbate existing disparities in pediatric oral healthcare.

## 5. Perspectives

The burgeoning landscape of emerging technologies is reshaping paediatric dentistry and early orthodontic treatment, heralding a new era for compliance management. Innovations like social media, mobile apps, advanced computing, and particularly AI are revolutionizing how we manage treatment compliance in young patients. AI is causing a paradigm shift in remote compliance monitoring, offering more effective behavioural management and personalized treatment strategies for patients. As these technologies evolve, we anticipate a significant shift towards proactive, patient-centered approaches with real-time data collection and analysis. This evolution will enable healthcare providers to intervene more effectively, adjusting treatment plans to optimize compliance and outcomes.

However, though these emerging technologies show considerable promise in improving compliance and treatment outcomes, their cost-effectiveness and accessibility must be critically evaluated to determine their practicality for widespread adoption [125]. The initial investment required for many of these technologies presents a significant barrier, particularly in resource-limited settings [126, 127]. For instance, the implementation of VR systems involves substantial upfront costs for headsets and content development, alongside ongoing maintenance [21, 22]. Similarly, AI-assisted remote monitoring platforms and sensor-embedded appliances incur expenses related to the hardware, software subscriptions, and data management infrastructure. Although these techniques may reduce the number of appointments and reduce long-term complications, and may save the cost of clinics and patients over time, high initial expenditures may limit their accessibility

[97, 128]. Therefore, the economic feasibility of these tools varies significantly across different practical settings. In well-funded private practices or institutional settings, the long-term benefits of improving patient compliance, simplifying workflows, and improving treatment efficiency may be a reasonable investment. However, these costs may be prohibitive for public health systems or practices in developing regions. This difference may expand the existing oral health quality gap between different socioeconomic groups.

In addition, with the introduction of a large number of intelligent technologies into compliance management technology, the protection of patients' personal data privacy is a potential research direction for future compliance management. The ethical imperative of data privacy and security must be central to development. The compliance management techniques should incorporate robust data privacy measures to protect the sensitive information of children and adolescents. Future development should focus on creating secure, user-friendly platforms that integrate with existing healthcare systems to enhance data management and patient privacy. While emerging technologies hold transformative potential for pediatric dentistry, future research must focus on data privacy to ensure their sustainable and secure integration into clinical practice.

Furthermore, a variety of minimally invasive treatment options have emerged to reduce the likelihood of invasive procedures and associated pain. Low-level laser therapy is a dual-purpose intervention that not only alleviates pain perception, but also serves as an innovative treatment for hard dental tissue diseases, thereby potentially reducing anxiety in paediatric and adolescent patients [129, 130]. As medical technology advances, we anticipate an increasing array of minimally invasive treatment methods and highly efficient treatment techniques to emerge. What is more, current research evaluates dental fear and treatment compliance in children and adolescents following behavioural management interventions primarily by scales and physiological measurements. Although different age-specific scales exist, their reliance on self-reporting by children or parents can introduce subjectivity [131, 132]. Physiological indicators, such as pulse and heart rate, offer an objective measure of dental fear and anxiety. In recent years, salivary cortisol and alpha-amylase have been recognized as more reliable biomarkers for assessing these conditions [133, 134]. However, inconsistent measurement techniques across studies hinder the direct comparison of results. Therefore, the development of standardized, objective, and practical measurement methods is critical to accurately assess dental fear and manage the treatment compliance of paediatric patients in the future.

In conclusion, research advancement across these domains (*e.g.*, digital technology, cost-effectiveness, data integration, minimally invasive treatments, and objective assessments) is expected to significantly improve chairside and remote compliance in children and adolescents. By shortening treatment duration and enhancing effectiveness, these innovations will ultimately improve the overall treatment outcomes in paediatric patients. The development and application of these innovative therapies will be critical in shaping a more efficient, effective, and patient-friendly future for paediatric dentistry and early orthodontic treatment.

## 6. Conclusions

This narrative review describes the key changes in compliance management techniques in pediatric dentistry driven by the integration of novel technologies. Emerging tools, such as those from VR and AI to sensors and IoT, are integrated into behavioural management strategies to transform compliance management from a clinical-centred reactive challenge to a proactive, continuous and patient-involved process. The evidence synthesized herein confirms that technology-enhanced strategies can significantly alleviate dental anxiety and optimize compliance, thereby improving the effectiveness and experience of pediatric dentistry and early orthodontic treatment.

However, the transformation of these promising technologies into daily practice requires considerable long-term development. Validation of these techniques is limited by small-scale research, significant methodological heterogeneity, and a lack of long-term outcome data. Therefore, future research must give priority to large-scale, longitudinal randomized controlled trials, not only to verify the efficacy, but also to strictly assess long-term cost-effectiveness, data security protocols and, equitable access. Ultimately, the future of pediatric behavioural management lies not in the technology itself, but in its thoughtful integration within a patient-centred care framework, guided by robust evidence and ethical considerations.

## 7. Limitations

There are several limitations to this review that should be acknowledged. As a narrative review, it may be subject to methodological constraints such as selection bias and variability among the included studies. In focusing specifically on research related to compliance management in pediatric dentistry and early orthodontic treatment, certain relevant studies may have been inadvertently overlooked or excluded due to the defined search parameters. Additionally, publication and language biases may have influenced the representativeness of the available evidence. Moreover, current research continues to exhibit notable gaps, particularly regarding long-term clinical validation and the standardization of compliance assessment methods. These limitations underscore the need for future multicenter and methodologically rigorous studies to further strengthen the evidence base in this evolving field.

### AVAILABILITY OF DATA AND MATERIALS

No datasets were generated or analyzed during the current study.

### AUTHOR CONTRIBUTIONS

CH and PLL—designed the article. CH, MMM, ZRY, YLZ and HYT—performed the literature search and data analysis. CH—drafted and wrote the main manuscript text. PLL, TT and ZHZ—provided help and advice on the research. All authors read and approved the final manuscript.

## ETHICS APPROVAL AND CONSENT TO PARTICIPATE

Not applicable.


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## CONFLICT OF INTEREST

The authors declare no conflict of interest.

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