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Digital workflow in orthodontics: a clinical overview for general dentists

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Abstract

Background and objectives: Modern dentistry is rapidly evolving with the integration of digital technologies aimed at enhancing the quality, convenience, and overall experience of care. Orthodontics is actively following this trend. The aim of this narrative review was to provide general dentists with a practical overview of digital orthodontic workflows by exploring the role of digital workflows in orthodontics, drawing from current and relevant literature to evaluate their impact on diagnosis, treatment planning, and delivery.

Findings: The findings highlight the growing expectation for clinicians to adopt digital workflows, emphasising the need for ongoing education and adaptation. Key areas covered in the literature include the use of intraoral scanners, 3D printing technologies, indirect bonding trays, and the rising popularity of clear aligner therapy.

Conclusions: While digital tools offer notable advantages such as improved accuracy, efficiency, and patient communication, they also present limitations including high initial costs, steep learning curves, and potential inaccuracies in specific applications. General dentists are recommended to adopt a critical yet proactive approach to the integration of digital technology into daily practice.

Introduction

The introduction of computer-aided designs (CAD) and computer-aided manufacturing (CAM) into dentistry first occurred during the 1970s (Harrell, 2018). Advances in digital technologies such as intraoral scanners and three-dimensional (3D) printers have been significant since their initial appearance in the industry, with the potential for promising results (Sannino *et al.*, 2014). Since then, demand and use of software purely designed to allow the study of electronic orthodontic models such as OrthoCAD™ (Cadent Inc., Carlstadt, NJ, USA) has been rising (Martin *et al.*, 2015). Digital tools and workflow have the potential to improve the quality and experience of both the clinician, patient, and laboratory time by producing faster, predictable, and convenient results. It enables immediate milling and printing procedures, as well as efficient designing via electronic software rather than traditional wax-ups. These advancements can benefit both orthodontists and general dentists by enhancing their clinical workflows and optimising their operations.

The complete digital workflow involves three key components: (1) acquiring visual data via intraoral scanners, (2) utilising a compatible software to manipulate this electronic data, and (3) manufacturing the designs via additive printing, or subtractive milling processes. In orthodontics, intraoral scanners (IOS) are used in a variety of applications such as treatment planning, fabrication of indirect bonding trays, clear aligners, customised lingual and palatal devices, and orthognathic surgery simulation (Martin *et al.*, 2015; Christopoulou *et al.*, 2022).

Despite the advantages presented by the digital workflow, not all clinicians implement technology in their clinical work. This may be attributed to their limited understanding of its uses, lack of experience with operatory systems, and the costly expenses associated with it (Mangano *et al.*, 2017; Cunha *et al.*, 2021). The objective of this article is to outline the clinical uses of digital workflow in orthodontics and evaluate the existing body of literature concerning various systems available in the field of digital orthodontics. It will also provide understanding and some relevant details of the digital workflow and how it can benefit clinicians (summarised in Table 1).

3D scanning and visual data acquisition

Replacing traditional casting with IOS has revolutionised the workflow within the dental profession. Due to the numerous IOS available in the market, consideration should be directed towards selecting an appropriate scanner for its intended use for effective application. IOS operates via emitting a laser or structured light source onto the dentogingival tissues which are then captured by imaging sensors (Mangano *et al.*, 2017). The CAD software then analyses this data and forms point clouds in triangulations, generating a 3D mesh model (Mangano *et al.*, 2017). A recent transnational questionnaire reported more than 75% of the participants used IOS daily in their clinical practice for general dentistry (Table 1) (Al-Hassiny *et al.*, 2023). This is in replacement of the conventional casting technique via alginate or polyvinyl siloxane impressions. The accuracy of traditional impressions depends directly on the operator's skills in placing the impression trays evenly across the dental arch. Slight misplacement or movement of the impressions often results in distortions reducing the accuracy. Other factors that cause the inaccuracy of traditional impressions include overall composition, distribution, homogeneity, and storage conditions of the impression; as well as casting time, material shrinkage, and temperature sensitivity (Mangano *et al.*, 2018). IOS has proved to eliminate many of these shortcomings.

The achievable accuracy stands as a crucial factor when evaluating the benefits of direct intraoral digitisation

Table 1. Summary of main findings of this review

Category	Key Finding	Reference(s)
3D scanning and visual data acquisition	1. Intraoral scanners (IOS) offer high accuracy and eliminate limitations of traditional impressions.	Mangano et al., 2017; Mehl et al., 2009; Al-Hassiny et al., 2023
	2. IOS improves patient comfort, especially in paediatric and gag-sensitive populations.	Ahlholm et al., 2018; Bosoni et al., 2023; Chalmers et al., 2016
	3. Scanner choice should consider speed, ergonomics, and file compatibility (e.g., STL).	Martin et al., 2015; Turkyilmaz et al., 2020
Operator experience with IOS	1. Scanner type and clinician experience affect learning curve and accuracy.	Kim et al., 2016; Revilla-León et al., 2023a; Thomas & Jain, 2023
	2. Training enhances scanning accuracy and helps manage patient-related challenges.	Revilla-León et al., 2023b; Róth et al., 2020
	3. IOS integration boosts workflow and aligner case volume but requires financial and training investment.	Davidowitz & Kotick, 2011; Mackay et al., 2017; Ali & Miethke, 2012
Manufacturing orthodontic appliances	1. 3D printing (DLP and LCD) allows in-house appliance fabrication, reducing lab dependence.	Ergül et al., 2023; Fayyaz Ahamed et al., 2015
	2. DLP is more accurate; LCD is faster and cost-effective for general practice.	Tsolakis et al., 2022; Venezia et al., 2022
	3. Printer selection should balance accuracy, speed, and material/support costs.	Tsolakis et al., 2022
Indirect bonding trays	1. Indirect bonding improves bracket accuracy and reduces chair time.	Silverman et al., 1972
	2. 3D-printed trays allow precise planning and bracket placement.	De Oliveira et al., 2019; Bachour et al., 2022
	3. Tray material (silicone, 3D-printed) affects accuracy; 3D-printed options are cost-effective and practical.	Gange, 2015; Sabbagh et al., 2022
Clear aligner therapy	1. Aligners are effective for mild-moderate cases, offering better comfort and hygiene.	Ali & Miethke, 2012
	2. 3D-printed aligners are more dimensionally stable and mechanically stronger than thermoplastics.	Jindal et al., 2019; Ryu et al., 2018
	3. Limitations include patient compliance and challenges with complex malocclusions.	Weir, 2017; Ryu et al., 2018

compared to traditional impression methods. The accuracy of IOS in restorative dentistry has been more extensively investigated, and many studies have validated its clinical acceptability (Ahlholm *et al.*, 2018). Studies have suggested that the accuracy of intraoral cameras can reach up to 19 μm in single-tooth images and quadrant images (Mehl *et al.*, 2009). Orthodontic treatment often requires full arch scans and many studies now support its adequacy with and without brackets (Moon and Lee, 2020; Song and Kim, 2020; Kang *et al.*, 2021; Kim *et al.*, 2021).

However, conflicting studies also exist and claim that arches with orthodontic brackets showed an increased average surface error compared to those without brackets (Kim *et al.*, 2021). Another study purely focused on the accuracy of scanning brackets and their slot angle in different bracket materials via four different intraoral scanners (Shin *et al.*, 2021). The study found that certain scanners produced more accurate results, indicating the essence of investing in the right type of scanners for general dentists when they consider purchasing an intraoral scanner. Polycrystalline brackets had the highest precision due to their characteristic of less reflection of light whilst other bracket types had higher errors. However, it is important to note that digital scanning still produces a superior result as the use of conventional impressions would be extremely difficult to identify the bracket slot base angle (Shin *et al.*, 2021).

There is also an existing doubt that intraoral scanners do not accurately capture the intricate details of severe malocclusion due to the effects of crowding or those with orthodontic appliances. However, dimensional differences between intraoral scans and alginate impressions were found to be clinically insignificant for orthodontic purposes even for capturing mixed dentition arches. This is significant because mixed dentition arches often involve crowding with numerous eruption complications, and orthodontic appliances such as mini-screws, bands, and wires with distalisation devices (Liczmanski *et al.*, 2020). The only limitation reported from the study was the size and shape of the scanner head. The study found that it was challenging to access posterior molar areas in individuals with small oral cavities and could not scan the distal surface of the most distal molar (Liczmanski *et al.*, 2020).

Most studies involving IOS and orthodontic scanning showed errors below 50 µm, which is clinically acceptable for treatment planning and diagnosis for orthodontic treatment (Moon and Lee, 2020; Song and Kim, 2020; Kang *et al.*, 2021; Kim *et al.*, 2021). Intra-arch linear dimensions to be used for Bolton analysis and measurement of intercanine width can also be consistently achieved (Naidu and Freer, 2013; Suryajaya *et al.*, 2021). However, there is potential for errors of more than 50 µm to have a significant impact on orthodontics, as treatments such as interproximal enamel reduction (IPR) are performed in the ranges of 100-500 µm per tooth. Excessive reduction due to planning errors following scans with error can lead to complications such as hypersensitivity, damage to the dental pulp, and increased risk of interproximal caries (Lapenaite and Lopatiene, 2014; De Felice *et al.*, 2020). In addition, differences in the thickness of 50-100 µm can alter occlusal contacts (Gintaute *et al.*, 2020). To put the measurements into perspective, the standard articulating paper used for restorative adjustments is 80 µm thick to ensure correction of high restorations following prosthodontic treatment. High restorations that create occlusal interferences are known to have potential damage to TMJ and dental structures (Lima *et al.*, 2010). Whether errors in thickness of 50 µm can have a significant clinical impact on the outcome of orthodontics needs further investigation. Further studies also have to be conducted to verify the accuracy of IOS bite registration in orthodontics.

Patient compliance is higher with IOS as it removes the discomfort and unpleasantness of impression materials (Mehl *et al.*, 2009; Ahlholm *et al.*, 2018). Advantages with comfort are particularly beneficial for young patients who also showed a significant preference for digital impressions, the common demographic seeking orthodontic treatment (Table 1). This is likely due to its less invasiveness compared to traditional impressions as it shows an improved outcome in reduced gag reflex, comfort, and breathing difficulties (Bosoni *et al.*, 2023). It was also found to be more compliant for patients with cleft lip and/or palate, and individuals with a sensitive gag reflex (Yuzbasioglu *et al.*, 2014; Chalmers *et al.*, 2016; Mangano *et al.*, 2018). In contrast, some pools of participants have preferred conventional impressions, mainly due to the interference of scanner tips with the coronoid process when capturing the posterior teeth of the upper arch (Moon and Lee, 2020). However, one can assume interference may differ according to the patient's anatomy, as well as the operator's ability to manipulate the patient's jaw opening and space. Additionally, many scanner tip and body sizes differ and there is certainly a potential for new scanners to be developed with progressively smaller sizes.

Integrating IOS in the clinical setting effectively requires learning the relevant technological skills and investing in the necessary digital resources. Selection of digital equipment should be based on the equipment's scanning speed, ease of use, size and ergonomics, annual subscription fees, open or closed CAD compatibility, autoclavable tips, and therefore the overall cost (Martin *et al.*, 2015). Perhaps the most relevant feature is to consider whether the scanner is compatible with an open interface system that enables it to be outsourced if the manufacturing of appliances will be done via an external lab (Westerlund *et al.*, 2015).

Once the IOS has recorded the optical measurements of the patient's arch, it generates a surface topography via triangulation meshes that are saved as a standard triangulation language (STL) format file. This data can then be exported to external orthodontic labs where it can be accessed through various CAD software that can manoeuvre the 3D images. STL is the most commonly utilised format as it is universally compatible with most other digital equipment and software (Turkyilmaz *et al.*, 2020). However, it lacks detail in that it is monochrome and does not capture the colour and texture (a colour that varies with location), making it difficult to distinguish between different anatomical structures such as the tooth and the gingival tissues. Other file formats exist, including polygon file format (PLY), and object file (OBJ) (Turkyilmaz *et al.*, 2020). Currently, the most widely utilised file format in orthodontics is the STL format for its compatibility and ease of use as outlined.

Virtual 3D images enable orthodontists to quickly obtain relevant information for diagnoses such as overjet, overbite, arch perimeter and width, tooth size discrepancy, and occlusal discrepancies (Harrell, 2018). 3D visual images of the occlusion, the ability to preview predicted results, and being able to share these data electronically with patients improve communication of treatment plans which may result in greater patient case acceptance (Mangano *et al.*, 2017). There are various orthodontic cast software available on the market, each with its pros and cons. Proper training is required to optimise workflow (Table 1). A study has concluded that OrthoCAD™ (Cadent Inc., Carlstadnt, NJ, USA) and O3DM (OrthoLab Inc., Poznan, Poland) were considered the most user-friendly out of a limited selection of orthodontic cast software (Westerlund *et al.*, 2015). All of the software scrutinised in this study provided more or less similar features. The study recommends professional training by experts for beginners as the usability of all of the systems was poor.

Operator experience with IOS

Operator experience with IOS was shown to vary between young and older dentists. The difference in user experience between dental students and experienced clinicians in taking both conventional and digital impressions has been compared (Lee *et al.*, 2013). Both groups had no previous exposure to digital impressions. The student group preferred digital impressions over conventional ones due to the greater patient comfort. They found conventional impressions to be much more technique-sensitive and difficult to obtain with accuracy. This observation aligns with the notion that clinicians with no previous training in digital impression techniques tend to adapt favourably, indicating that general dentists with no prior exposure to digital impression taking can easily benefit and use its workflow in their orthodontic practice. The senior clinicians were much more proficient at traditional impression-taking due to their experience. Additionally, results from the study indicate that experienced clinicians found the digital impressions equally challenging and no more difficult than the student cohort. This indicates that ease of use may mainly come from prior training for both experienced and inexperienced general dentists looking to integrate digital workflow into their practice. The senior clinicians also had a more balanced preference over the two impression methods (Kim *et al.*, 2016). One can only assume that younger clinicians were more well-accustomed to technology in general and therefore handled it with ease. The type of scanner used may also influence the operator's experience of digital scanning. According to Kim *et al*, iTero® (Align Technologies, San Jose, Calif) demonstrated a quicker learning rate compared to Trios (3Shape, Copenhagen, Denmark) scanners but the scanning time was longer with iTero than Trios on average (Kim *et al.*, 2016). Clinicians' experience also affected the usability of the scanner for iTero whereas it did not for Trios. Many studies claim that scanning time and accuracy are dependent on the clinician's technique and experience (Mangano *et al.*, 2017; Ahlholm *et al.*, 2018; Moon and Lee, 2020; Róth *et al.*, 2020). There are also studies that show scanning proves to be quicker than alginate impressions (Ahlholm *et al.*, 2018; Bosoni *et al.*, 2023).

Numerous studies have explored how operator skill affects scanning accuracy. One study showed that more experienced users completed scans more quickly, although their level of experience did not significantly impact the accuracy of scans performed with either the i500 or TRIOS scanners (Thomas and Jain, 2023). Another study supported this by noting that while greater experience improves scanning efficiency by reducing the time required, it may also enhance accuracy—particularly when using older models of intraoral scanners (Revilla-León *et al.*, 2023b). A study by the American Dental Association found that 82% of surveyed dental professionals received IOS training from the manufacturer of their purchased instrument, while 52% acquired skills through self-learning practice. Operators with greater experience had a better understanding and control over patient-related factors that influence scanning accuracy, including moisture management, capturing interdental spaces, arch width, the palate, existing prosthetic restorations, and edentulous areas (Revilla-León *et al.*, 2023a).

Even though digitization has become prevalent in numerous aspects of orthodontics, many dentists may still be apprehensive about making the move toward digital impressions. Notably, affordability is a concern with high initial purchase prices as well as ongoing maintenance costs (Martin *et al.*, 2015). Clinicians will need to invest time and effort into adjusting to the expertise required in successfully utilising the equipment, as inexperience can cause operator errors (Róth *et al.*, 2020).

Predominantly, digital scanning is most evidently utilised for clear aligner treatments. This is due to aligner companies relying on digital workflow to manufacture their products and may actively promote digital scanners for their operations. This presents a challenge for many dental laboratories that may lack the necessary resources for handling digital data (Ali and Miethke, 2012).

An interrupted time series analysis study followed 1,871 general practitioners and orthodontists internationally to observe increases in revenue from Invisalign® treatments following the introduction of iTero scanners into their practice (Mackay *et al.*, 2017). Results displayed a significant growth in patient acceptance of Invisalign®, with figures showing an increase of 5.92 treatments over the total participants for the first 12 months. Although a costly expense, the study shows orthodontic clinics will generate clear aligner cases with the use of IOS in clinics in the long run which can make it a worthwhile investment.

Unlike orthodontists, general dentists can obtain even greater benefits from investing in intraoral scanners (IOS), particularly in prosthodontics. Over the years, the integration of IOS with milling machines has revolutionised restorative dentistry by enabling the in-house production of ceramic indirect restorations. This advancement allows crowns to be fabricated within minutes to hours, replacing the traditional labour-intensive process that requires multiple appointments (Davidowitz and Kotick, 2011). As a result, intraoral scanners offer a multidisciplinary advantage for general dentists, making the investment highly worthwhile.

As previously outlined, a study identified Medit and Dentsply Sirona as the most popular intraoral scanner brands among the 36 different models reported in an international survey. The study, which analysed the experiences of 1,072 users, evaluated various factors including satisfaction, scanning speed, technical support, accessibility, and cost. These findings provide valuable insights for general dentists considering the transition to a digital workflow, helping them make informed decisions based on performance and usability (Al-Hassiny *et al.*, 2023).

The integration of intraoral scanners into general dental practice presents both opportunities and challenges. While financial barriers, workflow integration issues, and the need for staff training remain significant concerns (Ali and Miethke, 2012; Martin *et al.*, 2015; Moon and Lee, 2020), strategic implementation through comprehensive training programs, gradual adoption, and financial planning can facilitate the transition (Table 1) (Mackay *et al.*, 2017; Ahlholm *et al.*, 2018). Selecting the right IOS system that aligns with practice needs, coupled with patient education, can further enhance acceptance and efficiency. Addressing these challenges ensures a smoother transition, ultimately improving clinical efficiency and patient outcomes.

Manufacturing orthodontic appliances

The market for 3D printing in digital dentistry has expanded significantly, making it more accessible for clinicians to produce in-house orthodontic appliances. This technology complements the digital workflow in orthodontic care, allowing many orthodontists to bypass conventional laboratories and produce customised appliances more efficiently (Fayyaz Ahamed *et al.*, 2015; Ergül *et al.*, 2023). 3D printing, or additive manufacturing, builds objects layer by layer, ensuring precise geometries (Ergül *et al.*, 2023). Since its inception in 1986 with Charles Hull's stereolithographic (SLA) printers, various other systems, such as fusion deposition modelling (FDM), selective laser sintering (SLS), and digital light processing (DLP), have been developed. However, DLP and liquid crystal display (LCD) printers have gained popularity in orthodontics due to their speed and cost-effectiveness. While DLP uses light to cure resin in entire planes, making it faster than SLA, LCD technology directs light onto the build platform without optical expansion, avoiding pixel distortion. LCD printers offer a more budget-friendly option, particularly attractive for orthodontists seeking affordable 3D printing solutions (Tsolakis *et al.*, 2022).

Recent studies show that both DLP and LCD printers produce clinically acceptable orthodontic models (Fayyaz Ahamed *et al.*, 2015; Jaber *et al.*, 2021). However, DLP printers tend to offer better accuracy than SLA and LCD models (Lo Giudice *et al.*, 2022), though the differences are relatively minor, with all technologies meeting the clinical threshold for orthodontic appliance fabrication. A study demonstrated that DLP printers consistently outperformed LCD in accuracy, though LCD printers remain a viable option, especially considering their faster printing speeds and lower material costs (Tsolakis *et al.*, 2022). For general dentists integrating digital workflows, LCD printers, such as the Elegoo Mars Pro, are a cost-effective choice for producing orthodontic models, especially for less complex cases (Table 1) (Venezia *et al.*, 2022).

While layer thickness impacts the precision of printed models, the most significant factor for general dental practices is choosing a 3D printer that offers a balance between accuracy, speed, and cost. SLA, DLP, and LCD printers can all meet the clinical standards required for orthodontic model production, but LCD printers may offer the most practical advantages for general dental practices aiming to produce orthodontic appliances efficiently and affordably. General dentists should prioritize selecting a printer that aligns with their clinical needs and practice size, considering factors such as material costs, print speed, and support options.

Indirect bonding trays

The indirect bonding (IDB) technique, first introduced by Silverman, allows for the simultaneous bonding of multiple brackets to the entire arch, thereby enhancing accuracy and reducing chair time (Silverman *et al.*, 1972). This technique addresses common challenges in orthodontics, such as human error, tooth morphology variations, and soft tissue interference (Gange, 2015), improving bracket placement precision. With advances in digital technologies, clinicians now have the ability to create in-house 3D-printed IDB trays. These trays, combined with virtual planning software, allow for precise estimation of tooth movements by fusing intraoral scans and 3D CT scans, further enhancing the accuracy of bracket placement (Table 1) (De Oliveira *et al.*, 2019).

While the use of advanced 3D printers like SLA and DLP is essential for accurate IDB tray production (Groth *et al.*, 2018), the cost-effectiveness and practical implementation of these technologies must be considered. The choice of tray material, such as silicone, vacuum-formed, or 3D-printed options, influences both bracket transfer accuracy and overall efficiency. Research indicates that silicone trays generally produce the most accurate results, followed by vacuum-formed trays and 3D-printed trays (Bachour *et al.*, 2022; Gündoğ *et al.*, 2023). However, some studies argue that 3D-printed trays can offer comparable, if not superior, accuracy (Sabbagh *et al.*, 2022).

However, the cost-effectiveness of IDB, particularly through 3D printing, must be weighed against the clinician's assessment of its practical benefits. Though IDB is shown to improve bracket placement accuracy (Brown et al., 2015; Groth et al., 2018; Sabbagh et al., 2022), research suggests that both direct and indirect bonding techniques may still require adjustments to achieve optimal clinical results (Koo *et al.*, 1999; Li *et al.*, 2019) indicating that there is no conclusive evidence that it significantly enhances bracket transfer accuracy (Sabbagh *et al.*, 2022). For many clinicians, IDB may not be seen as a tool for increased precision but rather a matter of convenience. If a clinician finds the IDB process more streamlined and easier to operate, it may reduce the overall time spent during the bonding appointment, allowing them to see more patients and ultimately increasing practice revenue. Thus, the investment in IDB trays should be considered based on individual practice needs and how much the clinician values the time-saving benefits versus the initial cost of the equipment.

Additionally, there remains a gap in the literature regarding the specific errors that may arise from the use of IDB trays, though it can be inferred that printing errors could contribute to inaccuracies. Clinicians adopting 3D printing for IDB will need to develop the skills to identify misprints and make chair-side adjustments, ensuring the trays fit properly in the mouth. Furthermore, the learning curve for software design errors should not be overlooked, as clinicians will need to refine their ability to recognize and correct these errors in digital designs to improve outcomes and minimize adjustments.

Clear aligner therapy

The rise in the number of adult orthodontic patients has increased the demand for clear aligner therapies, which have the advantages of improved aesthetics during treatment, oral hygiene, comfort, and reduced additional urgent visits (Ali and Miethke, 2012). Clear aligners are generally used to treat mild to moderate crowding, including single or two-tooth intrusions, distal tipping of molars, and lower incisor extraction cases (Ali and Miethke, 2012). Severe malocclusions, including complex rotations, extrusions, molar uprighting, and closing premolar extraction spaces, while possible with aligners, are more challenging and require attachments or modifications such as bite ramps and pressure points to increase control (Ali and Miethke, 2012; Weir, 2017). Despite claims from various aligner brands that they can treat severe cases, there is limited scientific evidence supporting this (Weir, 2017). Thus, a strong understanding of aligner biomechanics is crucial for improving treatment predictability.

Aligners were originally designed via a labour-intensive manual process involving wax-ups and vacuum-formed retainers. This process has been largely replaced by digital simulations that generate progress models for aligner manufacturing. However, computerized treatment planning lacks limits, and as a result, proposed tooth movements can sometimes be unrealistic, particularly for complex cases.

Clear aligner therapy begins with digital intraoral scanning, which significantly reduces errors from traditional impression-taking (Jindal *et al.*, 2019). Advances in digital dentistry have also led to the possibility of directly 3D printing clear aligners, which avoids the cumulative errors associated with the thermoplastic workflow (Tartaglia *et al.*, 2021). However, studies indicate that aligners made via the thermoplastic process undergo material property changes due to heat generation. This can reduce the desired thickness and change the hardness of the aligners, which plays a key role in inducing tooth movement (Ryu et al. 2018). Researchers have observed variations in thermoplastic aligner dimensions, ranging from 0.5 to 1.5 mm (Ryu *et al.* 2018). Biomechanically, thicker aligners have increased flexural modulus and stiffness, which results in higher force, potentially affecting the accuracy of tooth movement (Tartaglia et al. 2021). Additionally, thermoplastic aligners can be responsive to environmental factors such as humidity, salivary enzymes, and temperature, which can alter their physical properties and clinical effectiveness (Tamburrino et al. 2020). These materials also exhibit a small degree of cytotoxicity due to the discharge of monomers during the heating process, especially with materials like Duran, Biolon, and Zendura (Martina et al. 2019). This potential cytotoxicity could pose risks to patients, and further research is needed to fully assess its clinical implications.

In comparison, a study measured the dimensional accuracy of 3D-printed clear aligners and compared those to conventionally made aligners (Jindal *et al.*, 2019). The printed aligners were made via Dental LT (R) (Long Term) clear resin (Form Labs, Somerville, MA, USA) material into 0.75 mm thickness and compared to Duran thermoplastic aligners. The authors reported that 3D-printed aligners had a higher dimensional accuracy. Furthermore, they were found to withstand higher loads while undergoing minimal displacement and exhibit elastic deformation at lower forces with reversibility. The study also found that LT clear resin had comparable mechanical stress qualities to Duran and Durasoft (Scheu-Dental GmbH, Iserlohn, Germany) in terms of nonlinear compressive forces mimicking human bite cycles. This validates the clinical potential for 3D printed aligners use as it has adequate mechanical strength to resist the forces of the oral environment without a decrease in clinical performance. Currently, there is no existing literature on the performance of Dental LT resin for clear aligners clinically and its longevity in the oral cavity.

Despite these promising advancements, several limitations exist with clear aligner therapy. One of the major challenges is patient compliance, as clear aligners require consistent wear, typically 20 to 22 hours per day, to be effective. Non-compliance can lead to delayed treatment and less predictable tooth movements. Furthermore, clear aligners are often not as effective at managing complex cases that involve severe rotations or extrusion and may require more adjustments than traditional braces (Table 1).

Another consideration is the higher cost of clear aligners, which can be prohibitive for some patients. The materials used in the production of aligners, combined with the need for advanced digital planning and monitoring, contribute to the cost. Clinicians must weigh the convenience and aesthetic benefits of aligners against their higher price points and limited effectiveness in certain cases.

In summary, clear aligners offer an aesthetic alternative to traditional braces and are highly effective for mild to moderate malocclusions. However, they are not without limitations, including challenges with patient compliance, unpredictable tooth movement, and cost. Additionally, although 3D-printed aligners offer promising mechanical properties, more clinical research is needed to understand their long-term effectiveness. When compared to traditional braces, clear aligners provide greater comfort and aesthetics, but they may be less effective for complex cases and are generally more expensive. Patient satisfaction tends to be high due to the aesthetic and comfort factors, but the overall cost-benefit analysis should be carefully considered by both clinicians and patients.

Conclusion

There is strong evidence for certain digital applications such as IOS and the use of 3D printing models for treatment planning. However, there is limited evidence on the benefits of indirect bonding trays, and 3D printing of clear aligners. Future research should aim to enhance the clinical accuracy of IOS and 3D-printed products, as well as explore the potential for 3D-printed aligners.

Author contributions

Conception or design of the work – CM, FF
Data collection and interpretation – OJ
Drafting the article – CM, FF
Critical revision of the article, final approval of the version to be published – all authors

Conflict of interest

The authors declare no conflicts of interest.

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