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Original Research Article

Mechanical and physical properties of attachments employed in clear aligner treatments. A critical appraisal

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Abstract

Introduction: Clear aligners have become a viable option for orthodontic treatment. Unlike conventional orthodontic brackets, aligners are not directly bonded to teeth and thus, have a different application of forces. Attachments are a type of auxiliary for aligner treatment that creates points in which pressure can be applied on the tooth surface, acting to transmit forces from the aligner tray to the teeth. Currently, there is no consensus on what material should be used to fabricate attachments and how they behave clinically. **Material and methods:** The present study is a critical appraisal of data already published on the subject up to now: from 1784 records initially screened, 11 reports were included, mostly *in vitro* studies and with variable methodology. Results: Surface wear of attachments can vary from 9,6% to 100%. Attachment loss is roughly the same for upper and lower arches, but posterior teeth tend to present more losses. Patient-related variables might account for more failures than operator and material-related failures, but it has been shown that conventional composites might present better resistance, aligner fitting, and less surface wear. **Conclusion:** Clinicians might expect some degree of attachment surface wear and losses. Patient orientation and use of conventional composites with high filler content might reduce such failures and improve treatment results.

Introduction

Clear aligner treatment has emerged as a viable clinical asset for the correction of several dental malocclusions. At first, this approach was applied in the correction of small dental malpositions and only minor movements could be achieved. The initial proposal made by Kesling [22] utilized a rubber device made from dental cast setups. Each setup was slightly different from the previous one, in that the malocclusion was gradually corrected, seeking an ideal dental position. This concept was applied three decades later by Ponitz [30], with the use of a device to heat plastic sheets which would be then thermoformed with vacuum pressure over dental casts.

The first commercial clear aligner system was introduced by Sheridan in the early 90s. This product consisted of a plastic thermoformed sheet that could be used as a retainer or in small dental movements. Its name, Essix, was an acronym for S-Six [Sheridan´s Simple System for Stabilizing the Social Six) in a reference to the indications of this technique and its limitation to teeth stabilization and small movements in the region of canines and incisor teeth [34].

The manipulation of 3D dental models in software that use Computer Aided Design (CAD) technology was first used in dentistry with finite element models. The technique was originally used for the analysis of mechanical stress in aeronautic equipment in the fifties [37] and allows the creation of digital constructs built from a triangle mesh that would present structural similarity with the object being studied. As a result, different simulations could be performed by adjusting the parameters in specific software. The technique saw increased application in dentistry in the 1970s for the analysis of mechanical stress in restorations with resin composites and amalgam [9, 12], evaluation of the dissipation of occlusal forces on teeth [33], alveolar bone [19] and dental implants [40].

In subsequent decades CAD became associated with Computer Aided Manufacture (CAM). The CAM technique allows for models designed in software to be manufactured by subtraction process in resin or zircon blocks [27] or by addition of photoactivated resin in the stereolithography technique [7].

In the late 90s, digital setups that would allow for individual movement of teeth were being employed. This would make possible the repositioning of these teeth, aiming to correct malocclusions. In 1997, Align Technology was founded and in the following year it launched its flagship product, the orthodontic clear aligner system Invisalign. Using CAD in its digital planning software clincheck and mass manufacture of dental models with the stereolithography technique, the planning and execution of low and intermediate complexity cases with orthodontic clear aligners became viable for orthodontists for the first time [6].

Currently, the workflow in a clear aligner treatment consists of the acquisition of a 3D digital model by means of an intraoral scanner. The model then goes through a process in which teeth are virtually segmented from the alveolar bone and gingiva to allow for repositioning individual and groups of teeth in the three-movement axis with a planning software. In this manner, movements such as rotation, extrusions, intrusions, translation, and angulation can be achieved. The quantity of dental movement and limits in each treatment stage can be adjusted in degrees or millimeters, according to the needs and limitations of the case in question. Intermediate movement stages are then programmed to allow for the digital setup to evolve from the initial malocclusion to the final objective programmed previously. Virtual planning can be performed by the orthodontist in free or paid software, or delegated to a technician from a company such as Invisalign or many others in the market. In this case, the technician will follow the orthodontist's instructions and the final planning will be approved by the responsible professional before the aligners are manufactured. The 3D impression and thermoforming of aligners can also be made by the orthodontist and his staff in-office or delegated to a third-party partner.

At present, in-office aligners have become a viable option for the clinician that is willing to invest in the equipment and necessary learning. The cost-benefit of in-office aligners depends on the number of aligners required to treat the case, which would depend mainly on the complexity of the malocclusion. Additionally, it requires the clinician to understand the planning stages in CAD software, and the 3D impression and aligner tray production process. This could be time and resource demanding and as such, in-office technique is most frequently seen in the treatment of low complexity cases, small tooth movement relapses, and discreet refinement of more difficult cases.

It has been reported that clear aligner therapy may provide benefits to patients such as less discomfort than conventional brackets, less aesthetic compromise of the smile during treatment, and ease in maintaining oral hygiene during orthodontic treatment. Due to better oral hygiene maintenance there seems to be fewer negative effects on the periodontium, making it an interesting approach in cases of patients with periodontal problems or higher risk of enamel demineralization [2, 4, 14, 21].

To overcome inherent limitations with dental movement utilizing clear aligners, attachments are utilized as auxiliary resources. These are buttons made from resin composites adhered to the tooth surface. They work as a force application point for the aligner to perform more unpredictable movements, such as rotations, extrusions and root control [13 23, 28]. Attachment loss or failure might result in treatment delays or inefficient tooth movement impairing the final result, and due to this, materials utilized for attachments must be able to withstand wear caused by chewing, aligner tray insertion and removals, and orthodontic forces.

Based on the current literature, this study performs a critical appraisal of the methods for evaluation of attachment integrity, or the clinical performance of materials utilized in attachments. The purpose of this critical review is to assess and categorize information already published on the subject.

Material and methods

Inclusion and exclusion criteria

Studies published up to March 2023 that evaluated attachments properties and materials and methods utilized in fabrication of attachments were included. Case reports, series of cases letters and systematic reviews were excluded.

Search strategy

Three databases were utilized for this search.

The following search strategy was applied in the Pubmed, Embase and Medline databases with no restrictions related to date or publication language. On the 25th January 2023, the following query, was used in Pubmed:

(((“Invisalign”[All Fields] OR “invisalign aligner”[All Fields] OR “invisalign aligner treatment”[All Fields] OR “invisalign aligners”[All Fields] OR “invisalign appliance”[All Fields] OR “invisalign appliances”[All Fields] OR “invisalign attachments”[All Fields] OR “invisalign cases”[All Fields] OR “invisalign clear”[All Fields] OR “invisalign clear aligner”[All Fields] OR “invisalign clear aligners”[All Fields] OR “invisalign first”[All Fields] OR “invisalign first system”[All Fields] OR “invisalign group”[All Fields] OR “invisalign orthodontic treatment”[All Fields] OR “invisalign material”[All Fields] OR “invisalign patients”[All Fields] OR “invisalign system”[All Fields] OR “invisalign technique”[All Fields] OR “invisalign therapy”[All Fields] OR “invisalign treatment”[All Fields])) OR ((“clear aligner”[All Fields] OR “clear aligner appliance”[All Fields] OR “clear aligner appliances”[All Fields] OR “clear aligner in house”[All Fields] OR “clear aligner orthodontic”[All Fields] OR “clear aligner orthodontic treatment”[All Fields] OR “clear aligner system”[All Fields] OR “clear aligner systems”[All Fields] OR “clear aligner technique”[All Fields] OR “clear aligner technology”[All Fields] OR “clear aligner therapy”[All Fields] OR “clear aligner therapie”[All Fields] OR “clear aligner treatment”[All Fields] OR “clear aligners”[All Fields] OR “clear aligners therapy”[All Fields] OR “clear aligners treatment”[All Fields])).

In the Embase database, the query “‘invisalign’/exp OR Invisalign” OR “orthodontic aligner” OR “clear AND aligner” was used. And in the Medline database, the query “(Invisalign) OR (clear aligner) OR (orthodontic aligner)” was used.

Results

The search resulted in a total of 2,221 reports. After filtering duplicates and an initial screening of the titles, 29 reports were selected for abstract reading, and 11 were selected to be included in the review (figure 1).

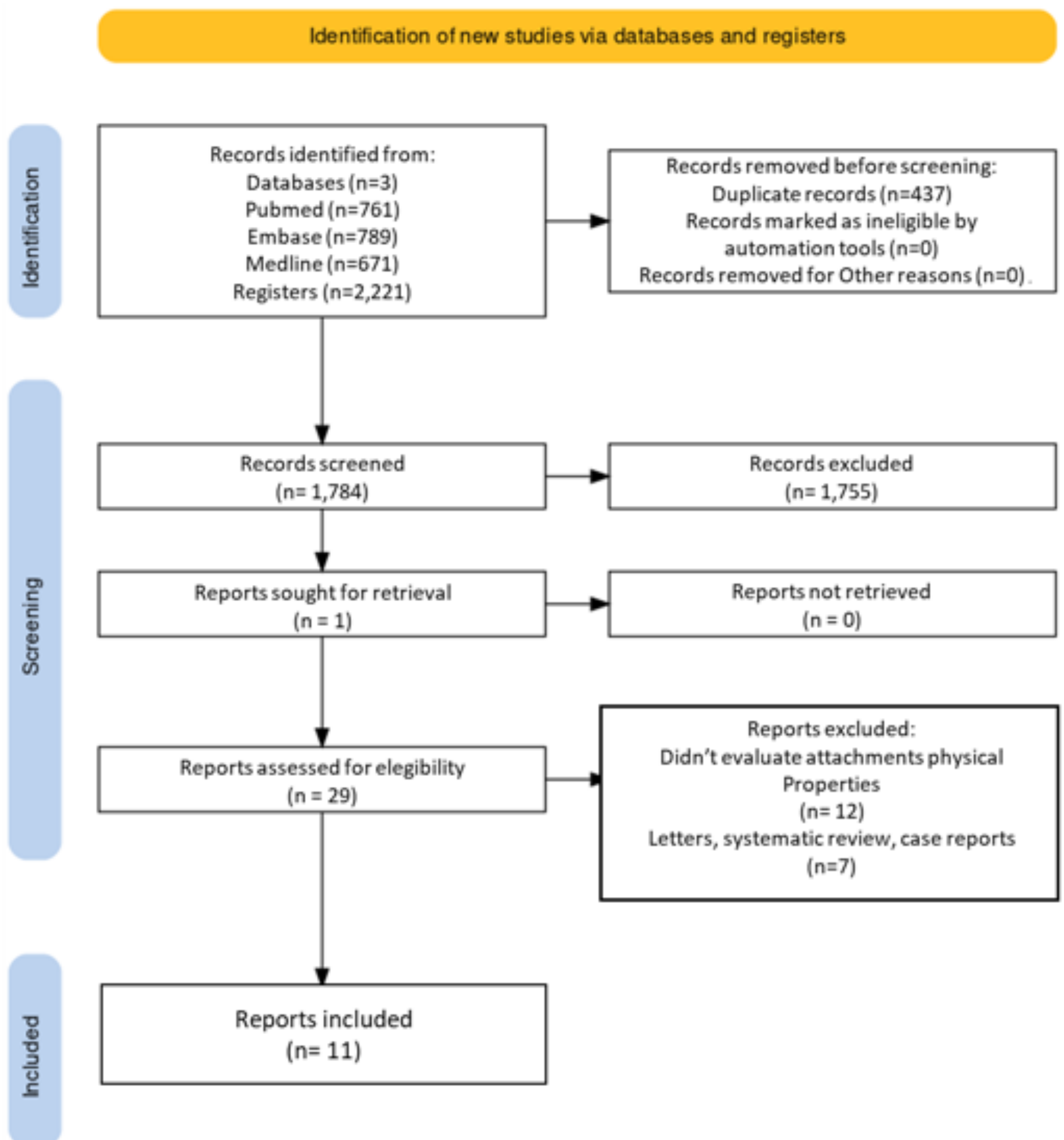

Figure 1 – Flowchart of the records identified and included for appraisal

Table I shows the selected paper, type of study, sample utilized, materials and independent variables, observed outcome, and evaluation method and results.

Table I – Records evaluating attachment behavior, and physical and mechanical properties

Article title	Author, year	Journal	Sample	Materials	Independent variables	Observed outcome	Evaluation method	Results	Comments
Surface wear of resin composites used for Invisalign® attachments	Barreda *et al.* (2019)	Acta Odontologica Latinoamericana	*In vivo* 10 patients 40 teeth	Filtek Z350 XT (CC); Amelogen Plus TW (CC); Single bond 2 (PR)	Composite	Attachment surface texture and shape	Scanning Eletron Microscopy	Attachment shape did not change significantly in a 6 month period. Amelogen plus exhibited greater surface wear.	
Influence of dental composite viscosity in attachment reproduction: an experimental *in vitro* study	D'Antò *et al.* (2019)	Materials	*In vitro* 75 attachments	Enamel plus HRi Flow (FC); Bracepaste (CC); Enamel plus HRI Enamel (CC); iBond Total Etch (PR)	Composite	Attachment shape defect, excess and volume	3D laser scan Model superimposition	Different viscosities (CC or FC) do not influence the shape and volume of attachments. FC showed less overflow.	
Scanning electron microscopy analysis of aligner fitting on anchorage attachments	Mantovani *et al.* (2019)	Journal of Orofacial Orthopedics	*In vitro* Six resin casts	Tetric EvoCeram Bulkfill (CNC); Tetric EvoCeram flow (FNC)	Composite Aligner tray material	Aligner fitting measured by attachment distance to aligner surface	Scanning Eletron Microscopy	Aligner fitting was improved by using CNC.	
Influence of attachment bonding protocol on precision of the attachment in aligner treatments	Weckmann *et al.* (2020)	Journal of Orofacial Orthopedics	*In vitro* 300 attachments	Two phase high-viscous composite; one phase low-viscous composite	Composite	Bonded attachment shape deviation from original model	3D laser scan 3D model superimposition	Both methods are reliable, but two-phase protocol is more precise.	
Assessment of preparation time and 1-year Invisalign aligner attachment survival using flowable and packable composites: a split-mouth clinical study	Lin *et al.* (2021)	The Angle Orthodontist	*In vivo* 52 patients	Filtek Z350XT Universal Restorative (CC); Filtek Z350XT Flowable restorative (FC); Adper Easy One (PR)	Composite	Attachment preparation time. Attachment survival rate.	Preparation time. Time to first observable attachment damage. Visual inspection of attachments	Flowable composite resulted in less preparation time but with slightly more damage rates.	

To be continued...

Continuation of table I

Article title	Author, year	Journal	Sample	Materials	Independent variables	Observed outcome	Evaluation method	Results	Comments
Comparative study of three composite materials in bonding attachments for clear aligners	Chen *et al.* (2021)	Orthodontics & Craniofacial Research	*In vitro* 129 mandibular premolars	Z35XT Flowable (FC); Z350XT and Sonicfill (CC)	Composite	Operation time Shear bond strength (SBS) Wear Resistance	Scanning Eletron Microscopy SBS test Optical Scan. 3D model superimposition	Flowable resin had more surface wear, volumetric change when installed and lower SBS.	
Risk factors of composite attachment loss in orthodontic patients during orthodontic clear aligner therapy: a prospective study	Yaosen *et al.* (2021)	BioMed Research International	*In vivo* 94 patients	Filtek Z350XT (CC)	Clinical variables, Operator-related variables, Patient-related variables	Main: attachment loss or breakage. Secondary: tray number, attachment position, frequency and method of tray removal and wear time, masticatory and eating habits, use of tray seaters and eating with or without aligners	Electronic questionnaire	Patient related variables accounted for 56,25% of attachment loss. Attachment position (on molar teeth), eating without aligners, use of tray seaters, frequent removal, low wear time and unilateral chewing correlate with more losses.	The patient would be responsible for observing attachment loss.
Light-curing process for clear aligners' attachment reproduction: comparison between two nanocomposites cured by the auxiliary of a new tool	Gazzani *et al.* (2022)	BMC Oral Health	*In vitro* 80 attachments	Tetric EvoFlow (FC); Transbond XT (CC). Assure Plus All Surface Bonding Resin (PR)	Composite, Curing light tip diameter	Attachment reproducibility; surface roughness and waviness	Digital Stereo Microscopy; Contact probe surface profiler	CC have more regular surfaces and better aligner fitting. Smaller light tip diameter improved attachment morphology.	

To be continued...

Continuation of table I

Article title	Author, year	Journal	Sample	Materials	Independent variables	Observed outcome	Evaluation method	Results	Comments
Bonding of clear aligner composite attachments to ceramic materials: an *in vitro* study	Alsaud *et al.* (2022)	Materials	*In vitro* 180 IPS e.max CAD teeth. 60 for surface roughness 120 for shear bond strenght	Filtek Z350 (CC); Filtek Z350 XT (FC); 9,6% Hydrofluoric acid (HFA), 37% phosphoric acid (PhA), Air abrasion (AA); Single Bond Universal bonding agent (SBU; PR); Assure Universal Bonding Resin (AUB; PR).	Composite, surface conditioning method, bonding agents	Shear bond strength, surface roughness	Universal testing machine	Air abrasion provided higher surface roughness. AA and HFA had more SBS than PhA. AUB provided more resistance than SBU. Packable composite provided more SBS than flowable.	
Performance of rigid and soft transfer templates using viscous and fluid resin-based composites in the attachment bonding process of clear aligners	Valeri *et al.* (2022)	International Journal of Dentistry	*In vitro* 24 samples	Transbond XT Light Cure Paste Adhesive (CNC); Tetric Evoflow (FNC)	Composite, attachments transfer trays	Attachment reproducibility	3D laser scanner Model superimposition	CNC has shown better reproducibility than FNC.	No etching and adhesive bonding step were performed because the bonding of attachments was performed on a resin model, not natural teeth.
Surface wear and adhesive failure of resin attachments utilized in clear aligner orthodontic treatment	Jardim *et al.* (2023)	Journal of Orofacial Orthopedics	*In vivo* 10 patients 125 teeth	Vittra APS Unique (CNC)	Attachment type (conventional/ optimized). Comparison between attachments in different groups of teeth (molar, premolar, anterior), and dental arch (Upper/lower)	Surface wear, attachment failure (Adhesive and cohesive)	3D laser scanner Model superimposition	Surface wear was present in 53% of the sample. Attachment loss was up to 24%. Attachments that are optimized, are on posterior teeth tend to have more cohesive failure. Adhesive failure was more frequently observed in conventional attachments and roughly equal for upper and lower arches.	

* CNC: conventional composites; FNC: flowable composites; PR: primer

Discussion

Attachments in clear aligner therapy

Clear aligner treatment is based on the principle of the application of forces with the objective of achieving controlled dental movement. Such forces can vary in magnitude according to the desired movement, material utilized in the aligner tray fabrication, tooth/teeth moved, and speed at which movements are planned [11, 15, 18]. The inherent biomechanical challenges that orthodontic treatment with aligners present has been highlighted previously. The limitations of clear aligner treatment include specific dental movements such as torque control, rotations of canines and premolars, vertical movements to correct deep bite, and intrusion of posterior teeth to correct anterior open bite [14, 18, 29]. As a response to such situations, auxiliary resources are employed which aim to complement the activation forces of aligners. Some of the resources that can be named are interproximal reduction of dental enamel, elastics, skeletal anchorage and most used of all, auxiliary devices known as attachments.

Attachments are important mechanical auxiliaries in clear aligner treatment [3, 23, 39] and their indication and positioning is set in the interface of the planning software [5, 14]. Fabrication is performed by printing a template model, over which a more flexible aligner tray will be thermoformed (template tray). This allows for transfer of the digitally planned attachments to the teeth crown by filling the spaces in the template tray with photoactivated resin composite and positioning them against the previously etched dental surface. Therefore, attachment shape, size and positioning will vary accordingly to the need of each treatment and dental movements [15, 32].

Attachment loss, whether due to adhesive or cohesive failure might result in delays in treatment and require more material and chairside time. Additionally, loss of tracking might occur, a situation in which tooth movement deviates from that planned in the CAD software. Clinically, it might be observed as aligner tray maladaptation, something that can also be observed in cases in which attachments are incorrectly manufactured. It has been reported that up to 14% of attachments might present shape alterations and this might relate also to the type of resin employed in attachment fabrication [3, 25].

Attachment failures

Attachments must be able to endure the constant stress caused by the remotion and insertion of clear aligners, buccal environment, and orthodontic force application [3]. At the same time, the material employed in attachment fabrication must be a compatible color with the dental enamel and minimal shape distortion when photoactivated. The resistance of attachments has been related to several factors, such as material, surface etching, and bonding technique [5, 39].

Failures in attachments can be classified as surface wear, cohesive and adhesive failure. Surface wear is the loss of material on the surface of an attachment with general structural integrity. Cohesive failure is the loss of structural integrity in which a fracture can be observed; it is a critical failure that occurs in the structure of the attachment and leads to a layer of adhesive remaining in the enamel surface (substrate). This indicates excellent adhesion despite the loss of integrity of the material. Adhesive failures are interfacial bond failures between the adhesive and the adherent, the attachment is lost due to *debonding* from the enamel surface [10].

Reports in the literature that analyzed the surface wear of attachments are scarce and methodologies vary. Lin *et al*. [25] observed that 9.6% of attachments in a patient sample presented some kind of damage after a follow-up period of 8 months using a visual observation method. On the other hand, the results from Jardim *et al*. [20] have shown surface wear of up to 53% in a sample with a 4-month follow-up when employing a 3D model superimposition method. Barreda *et al*. [3] have reported that in a sample of 40 attachments, all presented some kind of change when observed under Scanning Electron Microscopy.

Although it is questionable if low values of surface wear can have a clinical impact on the performance of attachments during treatment [25], adhesive and cohesive failure could certainly affect the clinical outcome since attachments under these conditions could be considered lost. Reports in the literature range from 6.7% to 24% of attachment loss [20, 40].

Interestingly, contrary to what is expected, there has been no difference in the number of attachments lost in the upper or lower arch reported, being roughly half the losses in each arch [20, 40]. This was not observed when comparing attachment loss in different groups of teeth (molars, premolars, and anterior teeth). Both studies reported more attachment loss in molar teeth, but Jardim *et al.* [20] reported that premolars have more losses than anterior teeth, and the contrary was reported by Yaosen *et al.* [40]. The increased frequency of loss observed in molar teeth could be explained by the higher mechanical and functional stress observed in this area, in which masticatory loads can be up to 53 kg [31], and by the difficulty and increased risk of contamination during attachment bonding.

Yaosen *et al.* [40] have also assessed that differing independent variables such as the use of aligner tray seaters, eating without aligners, frequent tray removal and low wear time, and unilateral chewing correlate with a higher frequency of attachment losses. Often, variables that are patient-related account for attachment losses when compared to clinical and operator-related variables such as age, gender, attachment shape, bonding materials, and protocols. The authors have highlighted that bonding failures will result in adhesive failure in a short time. This information can be useful for the clinician to assess if failure was due to an inefficient attachment bonding procedure or due to some other patient-related variable.

Variables such as aligner margin length and removal method also may indirectly relate to attachment loss during aligner removal. Takara *et al.* [35] tested the force required to remove an aligner and observed that longer margins cause the aligner to be more retentive, which may result in an increased force on attachments. Removing aligners as one unit and applying force on a single site could also lead to attachment damage. The authors suggested that initially removing an aligner from the lingual region of molars and then lifting it from the contralateral region might be easier and less damaging on attachments.

Only one study [1] evaluated the bonding of attachments to non-enamel surfaces. When bonding attachments to e-max CAD teeth, hydrofluoric acid, and air abrasion are the preferable methods for surface etching over conventional phosphoric acid. In accordance with other studies in this review, conventional packable composites provided more shear bond strength than flowable composites.

Use of conventional composite or flowable composite

A recurrent question among clinicians is whether conventional composites with high filler content are more appropriate than flowable composites with less filler content for the fabrication of attachments. Composite resins are a mixture of organic and inorganic components. Organic components are usually the resin, coupling agent initiator, and filler. Fillers are responsible for important mechanical properties such as strength, hardness, polymerization shrinkage, thermal expansion, and workability.

Flowable resins tend to have lower filler content, which results in greater viscosity at the cost of other mechanical properties. Lin *et al.* [25] observed that flowable composites have shown significantly less preparation time than conventional composites. And although it could be hypothesized that flowable resins would present more smooth surfaces and more accurate attachment shapes, studies have shown that conventional composites have more regular surfaces and better aligner fitting [16, 26, 37] and that composite viscosity is not related in a significant manner to shape accuracy and volume of attachments [5, 8]. On the other hand, in agreement with previous studies on flowable composites, the use of low filler materials results in attachments with less shear bond strength and higher surface wear than conventional composites [1, 5, 25].

Evaluation methods

Previously published studies evaluating the clinical and physical properties of attachments employed in clear aligner therapy applied a variety of methods. Previous authors [5, 8 38, 37] made evaluations with the aid of 3D models acquired with a scanner and superimposed to assess attachment shape and surface wear. Scanning electron microscopy and digital stereo microscopy have also been used with the same objective in other studies [5, 16]. The use of 3D models has the advantage of being a non-destructive form of analysis, the files can be exported, and different tests can be done by a wide array of software. And although none of the authors have done any *in vivo* testing, ongoing research in the process of publishing has employed this method for studying attachments in patients. Currently, 3D model analysis and superimposition is a fast and reliable method and ongoing research has employed free software which makes this method available for any researcher independent of funding.

Lin *et al.* [25] utilized visual inspection of attachments to evaluate attachment survival rate. This is a simple and fast method to observe more obvious failures, such as cohesive and adhesive failure, but it may not have the precision required to evaluate more discreet changes such as surface wear.

If other variables are to be analyzed, such as shear bond strength and surface roughness and waviness, methods such as a universal testing machine or a contact probe surface profiler could be utilized [1, 16].

Limitations

The study of dental materials is inherently difficult because many variables can only be accurately observed *in vivo*. This can lead to a gap between what is observed in a controlled environment and what happens in a clinical setting. Nevertheless, this information is valuable and crucial to assist clinicians in their decision-making process and the critical appraisal performed here can help clinicians on their decision-making process regarding their material of choice.

Clear aligner therapy is a recent treatment modality and research in this area is still ongoing. Few studies have assessed the physical properties and performance of attachments. Due to new methods of 3D superimposition, it is now possible to evaluate attachment changes with greater accuracy, as well as creating a possibility to evaluate *in vivo* some mechanical properties such as surface wear and failures.

We believe future studies would benefit from employing techniques that rely on 3D models and intra-oral scanning to acquire data with the precision of an *in vitro* model in a *in vivo* setting.

Conclusion

- Surface wear in attachments can have a frequency of 9,6% to up to 100% depending on the material employed. But it is unknown to what extent this could impair the clinical outcome and efficiency;
- Attachment loss is roughly the same for upper and lower arches, but molar teeth tend to have more losses;
- Patient-related variables such as removal method, wear time and use of tray seaters might account for more attachment failures than clinical, and operator related variables;
- Conventional composites have better resistance and less surface wear, more regular surfaces, and result in better aligner fitting.

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