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Wear volumes of flowable and sculptable resin composite attachments and their correlation with retentive force of clear aligners: a laboratory study

Nuttakan Roatkanjanaporn[1], Janeta Chavanavesh[1*] and Chutimont Teekavanich[1]

Abstract

Background Aligner attachment integrity is important for clear aligner retention and overall treatment efficacy. This study aimed to evaluate the wear volume of clear aligner attachments and the retentive force change of clear aligners over a simulated 24-week insertion/removal period, along with their correlation.

Methods Attachments made from Tetric N-Flow (flowable), Beautifil Injectable X (flowable), or Filtek™ Z350 XT (sculptable) resin composites (n = 6 each) were bonded to the first premolars of maxillary dental resin models. Each model underwent a simulated 3-cycle daily insertion and removal of 12 clear aligners, with each aligner tested for 14 days, using a universal testing machine. Attachment wear volume was quantified through 3D scanning and superimposition. Average daily retentive force of aligners was measured. Data were analyzed using mixed-design ANOVA to evaluate differences in retentive force and wear volume among composites, and Pearson's correlation to assess the relationship between wear and retentive force change. Statistical significance was set at $p < 0.05$.

Results Significant attachment wear was observed primarily in gingival regions, without significant differences in wear volume among the three composites. Retentive force decreased significantly from days 1 to 2 and continued to decline until day 14 ($p < 0.01$), without significant differences in retentive force among aligners nor composite types. No significant correlation was found between attachment wear volume and the retentive force difference between the 1st and 12th aligners.

Conclusions Despite reductions in attachment volume across all three composites over the 24-week period, no significant change in mean retentive force among aligners was observed. The tested composites demonstrated comparable wear resistance during repeated aligner insertion and removal over 24-week, with stable aligner retentive force, supporting their feasibility for use in clear aligner therapy.

Keywords Wear, Attachment, Resin Composite, Clear Aligners, Retentive force

Background

Clear aligners have become a discreet and convenient alternative to traditional braces, due to their aesthetic appeal and comfort [1]. Initially designed for minor tooth movements using transparent thermoformed plastic [2], clear aligner therapy has rapidly advanced in both materials and techniques over the past decade.

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These innovations, along with the development of auxiliary tools such as miniscrew anchorages and attachments, have broadened the applicability of clear aligners to address increasingly complex malocclusions [3, 4].

Attachments are small resin composite shapes bonded to the tooth surface to enhance aligner retention and facilitate tooth movement [4]. The shape, position, and fit of the attachments significantly influence both retentive force and the generation of effective force systems [4]. To achieve optimal outcomes, attachment materials should balance aesthetics, durability, and wear resistance over time.

Resin composites are made up of three primary components: an organic resin matrix, inorganic fillers, and a coupling agent. Flowable resin composites, with similar chemical components but lower filler loading than sculptable ones, were initially not recommended for high-stress situations [5, 6]. However, technological advancements have improved the wear resistance of certain flowable resin composites, making them viable options for attachment fabrication [7–9]. Lin et al. (2021) found that preparation time for attachments using flowable composite (6.22 s/attachment) was significantly shorter than for packable composite (32.83 s/attachment), with no statistically significant difference in their 1-year damaged rates [10]. The choice of attachment material often depends on the clinician's preference, with some opting for sculptable resin composite and others preferring a flowable one.

The clinical wear of clear aligner attachments is a complex phenomenon influenced by various variables, including the type of resin composite used, the abrasive surface, and the abrasive particles present [11]. Barreda et al. (2017) found that micro-hybrid sculptable resin composite (Amelogen Plus) has undergone more surface texture changes than nanofilled sculptable ones (Filtek™ Z350XT) after six months of clear aligner treatment, although no significant shape changes were observed in either group [12]. Cycles of stressing and unstressing can lead to cracks and material loss in attachment [11]. Therefore, repeated insertions and removals of aligners may contribute to wear, resulting in reduced retentive force, improper active surface function, undesired force systems, and unpredictable tooth movement.

Previous studies have indicated that aligner retention is influenced by factors such as the shape and position of attachments, the material and thickness of the aligner, and the design of the aligner margin [13–15]. Preliminary laboratory study revealed that following the initial aligner removal, there was a notable decline in retention, with the area of the aligner adjacent to the attachments showing visible stretching [16]. Retention then decreased gradually from the second to the tenth removal. However, after this point, there was no significant change in retention [16].

However, there was no study reporting the wear volume of attachment made of flowable resin composites, nor the relationship between wear and retentive force. Therefore, this study aimed to evaluate the wear volumes of aligner attachments made from nanohybrid flowable and nanofilled sculptable resin composites, assess the retentive force change of clear aligners, and investigate the correlation between wear and retentive force change over a 24-week period of simulated aligner insertion/removal. The null hypotheses of this study were:

1. There were no significant differences in attachment wear volumes among different resin composite attachments and different parts of the attachments.
2. There were no significant differences in clear aligner retentive forces among different resin composite attachments and across different days of clear aligner insertion and removal.
3. There was no correlation between the average change in retentive force and the overall attachment wear volume.

Materials and methods

The sample size was calculated based on the study by Gazzani et al. [17] using mean ± SD worn volume (mm^3) of flowable nanocomposite (0.030 ± 0.014) and conventional nanocomposite (0.002 ± 0.001), with a significant level of 0.05 and power of 80%, using G*Power 3.1.9.7 software (Heinrich-Heine-Universität Düsseldorf, Germany). The minimum sample size in each group was six.

The study samples consisted of occlusally beveled horizontal rectangular attachments placed on the mid-buccal surface of right and left maxillary first premolars across nine identical maxillary dental resin models ($n = 18$). Attachments were fabricated from three resin composites in translucent/incisal shade: Tetric N-Flow (Ivoclar Vivadent AG, Liechtenstein), Beautifil Injectable X (Shofu, Japan), and Filtek™ Z350 XT universal (3 M ESPE, USA), each with distinct compositions and handling characteristics (Table 1).

A well-aligned maxillary stone model was scanned using Ceramill® Map 400 and processed in Ceramill® Mind (Amann Girrbach GmbH, Austria), then further modified in Autodesk Meshmixer 3.5 (Autodesk Inc., USA) (Fig. 1).

In the first edit of the original image (Fig. 1A and B), a 5.5-mm diameter and 3-mm depth cylinder, representing a metal stop, was added to the occlusal surfaces of the first molars and palatal surfaces of the canines. An occlusally beveled horizontal rectangular attachment (height: 2 mm, width: 3 mm, depth: 0.25 mm occlusally

Table 1 Characteristics of resin composites used for attachment fabrication

Resin Composite	Lot Number	Resin Matrix	Filler	Filler load
Tetric N-Flow (Nanohybrid, flowable)	X41730	Bis-GMA[a] UDMA[b] TEGDMA[c]	Barium glass Ytterbium trifluoride Barium-aluminium fluorosilicate glass Si-Zr mixed oxide	63.8 wt% 39–40 vol%
Beautifil Injectable X (Nanohybrid, flowable)	111,901	Bis-GMA[a] Bis-MPEPP[d] TEGDMA[c]	Aluminofluoro-borosilicate glass	50–60 wt% 42 vol%
Filtek™ Z350 XT universal (Nanofilled, sculptable)	NA98501	Bis-GMA[a] UDMA[b] TEGDMA[c] PEGDMA[e] Bis-EMA[f]	Non-agglomerated/non-aggregated silica Non-agglomerated/non-aggregated zirconia Aggregated zirconia/silica cluster	72.5 wt% 55.6 vol%

[a] Bisphenol A Glycidyl Methacrylate

[b] Urethane Dimethacrylate

[c] Triethylene Glycol Dimethacrylate

[d] 2,2-Bis[(4-Methacryloxy Polyethoxy) Phenyl] Propane

[e] Polyethylene Glycol Dimethacrylate

[f] Bisphenol A Ethoxylated Dimethacrylate

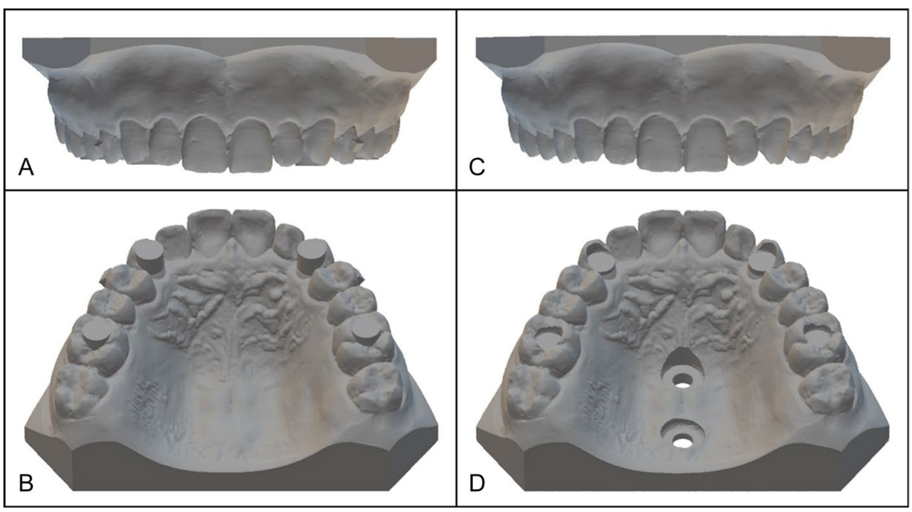

Fig. 1 3D images that have been modified for further printing. Front view (**A**) and occlusal (**B**) view of the first edited image. Front view (**C**) and occlusal (**D**) view of the second edited image

and 1.25 mm gingivally) was positioned at the center of the buccal surface of right and left first premolars.

In the second edit of the original image (Fig. 1C and D), two holes were drilled through the center of the palate between the first and second premolars and between the first and second molars. These holes facilitated fixation of the model to the universal testing machine (Shimadzu EZ test, Japan). Additionally, a hole measuring 5.5 mm in diameter and 3 mm in depth was created in the occlusal surfaces of the first molars and the palatal surfaces of the canines. These holes allowed for the placement of a metal stop attached to a metal rod (1.5 mm in diameter and 30 mm in length), which extended from inside the molars and canines through the thermoformed aligner and into the universal testing machine.

Attachment template and clear aligner fabrication

Nine models were printed based on the first edited image (Fig. 1A and B) using photopolymer resin (Formlabs Grey Resin V4, Formlabs, USA) at a resolution of 50 µm. Each model was then utilized with a vacuum thermoforming machine (Biostar®, Scheu Dental Technology, Germany) and thermoformed plastic sheet (Essix ACE 125 mm circle 0.035", Dentsply Sirona

Orthodontics, USA) to create an attachment template and twelve clear aligners. The sheets were vacuumed over the models according to manufacturing standards. Subsequently, the templates and clear aligners were trimmed with a straight-line margin extending from 1 mm cervical to the gingival zenith of the central incisors to the gingival zenith of the second molars.

Composite attachment bonding

Nine models were printed based on the second edited image (Fig. 1C and D) and were randomly divided into three groups according to the types of composite attachments. The models in group 1, 2, and 3 were bonded with Tetric N-Flow (tetric), Beautifil Injectable X (beautifil), and Filtek™ Z350 XT Universal (Z350) respectively. The resin composite was filled into the attachment windows of the template. The template was fully seated over the model, and the attachments were light-cured for 20 s (2000 mW/cm^2, Mini LED SuperCharged, Acteon, UK). The attachment surfaces were not polished after template removal.

Simulation of clear aligner insertion and removal, and measurement of retentive force

To install the metal rods onto the universal testing machine, their positions were set at 15.5 mm transversely and 10 mm anteriorly for teeth 13 and 23, and 25.5 mm transversely and 11 mm posteriorly for teeth 16 and 26, using the axial center of the machine as the reference point. The aligner was inserted and removed using a universal testing machine, with movements performed perpendicular to the occlusal plane (Fig. 2). After confirming the initial seating, a pulling force was applied at a constant rate of 6.35 mm/min with a 500 N load cell until the aligner was fully removed, then reinserted. This process was repeated 42 times for each aligner to simulate a removal and insertion routine performed three times daily for 14 days. Twelve aligners were used on each resin model to simulate a 24-week period. The universal testing machine recorded the minimum force required to remove the aligner from the resin model, representing the retentive force. Average retentive forces for every 3 cycles were recorded as the aligner retentive forces in days 1 to 14. The forces in days 1, 2, 7, 10, and 14 (D1, D2, D7, D10 and D14) of each aligner, and the difference

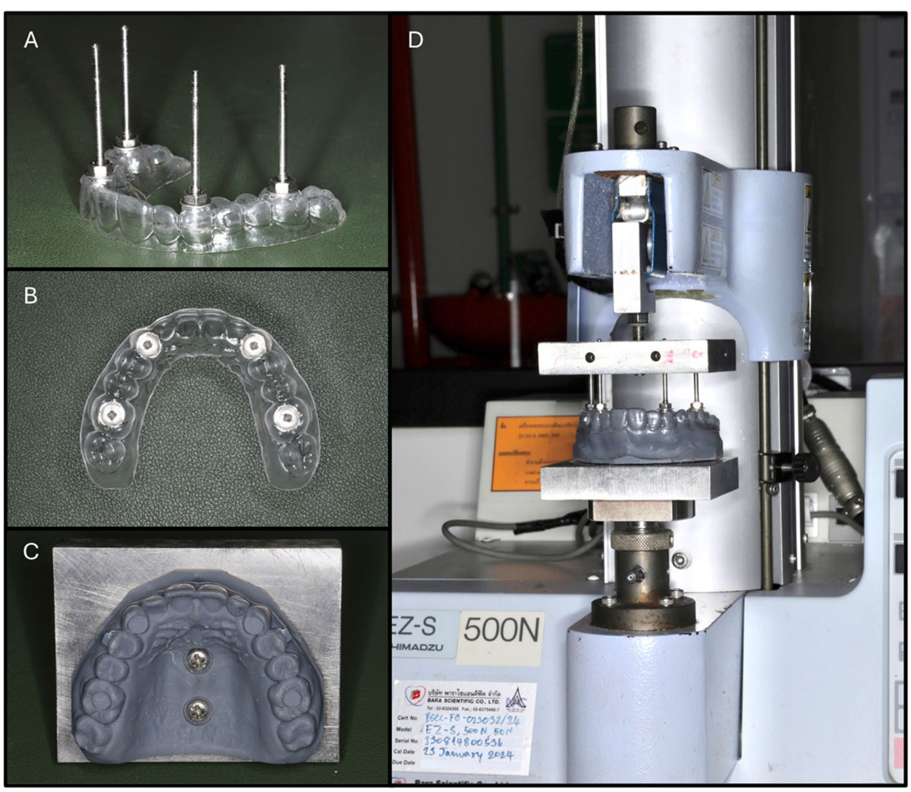

Fig. 2 The setup for aligner insertion and removal. **A** Metal stop rods were secured to an aligner. **B** A bottom view of the aligner showed metal stops positioned on the canines and first molars. **C** A resin model with resin composite attachments on teeth 14 and 24 was fixed to the base. **D** The sample was installed on the universal testing machine

between average retentive force of the 1st and 12th aligners were used for subsequent statistical analysis.

Measurement of wear volume

Resin models with composite attachments were scanned using a 3Shape Trios3® scanner (3Shape Dental System, Denmark) before and after repeated insertions and removals of aligners. The scan images were trimmed to focus on teeth 14 and 24. The before and after images were superimposed using the best-fit alignment function (Fig. 3A) in Geomagic Control X version 22.1.0.70 (3D Systems, Inc., USA). To quantify wear volume, the superimposed 3D images were exported to create solid models using Geomagic Design X, version 23.01 (3D Systems, Inc., USA). The attachments were divided into 9 parts, i.e. occluso-mesial (OM), occluso-middle (OMid), occluso-distal (OD), middle-mesial (MidM), middle-middle (MidMid), middle-distal (MidD), gingival-mesial (GM), gingival-middle (GMid), and gingival-distal (GD). The Boolean function subtracted the before models from the after models. The resulting residual models represented the wear volume of the attachments (Fig. 3B). The volume of each part was recorded for subsequent statistical analysis. Ten percent of samples were randomly selected for intra-observer reliability testing.

Statistical analysis

The data were analyzed using IBM SPSS Statistics version 22.0 (SPSS, USA) with a significance level set at $p < 0.05$. A mixed-design ANOVA with Tukey or Bonferroni correction post-hoc analyses were employed to assess mean retentive force differences between day, composite, aligner, and wear volume differences between attachment areas and composites. The relationship between wear volume and the average retentive force difference between the 1st and 12th aligners was investigated using Pearson's correlation. The intraclass correlation coefficient (ICC) was used to determine intra-observer reliability.

Result

Wear volume

ICC for wear volume measurement was 0.998. The mean and standard deviation (SD) of wear volumes were shown in Table 2. There was no significant interaction between attachment area and composite on wear volume ($p = 0.180$), nor was there a significant difference between composites ($p = 0.336$). However, a significant difference in wear volume was observed among attachment areas ($p < 0.001$).

Pairwise comparisons (Fig. 4) showed that GD had a significantly higher wear volume than OM (0.016 mm^3, $p < 0.001$), OMid (0.018 mm^3, $p = 0.001$), OD (0.015 mm^3, $p < 0.001$), MidM (0.012 mm^3, $p = 0.014$), MidMid (0.017 mm^3, $p < 0.001$), and MidD (0.017 mm^3, $p = 0.035$). GMid also had a significantly greater wear volume compared with OM (0.014 mm^3, $p = 0.015$), OMid (0.017 mm^3, $p < 0.001$), and MidMid (0.016 mm^3, $p = 0.023$).

Retentive force

The mean and SD of retentive forces were shown in Table 3. No significant interactions were found between day, composite, and aligner ($p = 0.270$); day and aligner ($p = 0.470$); or composite and aligner ($p = 0.265$) on retentive force. Additionally, there were no significant differences between composites ($p = 0.309$) or aligners ($p = 0.452$). However, a significant interaction between day and composite on retentive force was observed ($p = 0.020$), as well as a significant difference between days ($p < 0.01$).

Pairwise comparisons revealed that mean retentive force significantly decreased over the measured days (Fig. 5). Three composites demonstrated comparable retentive force on Days 1 and 2. Tetric showed lower

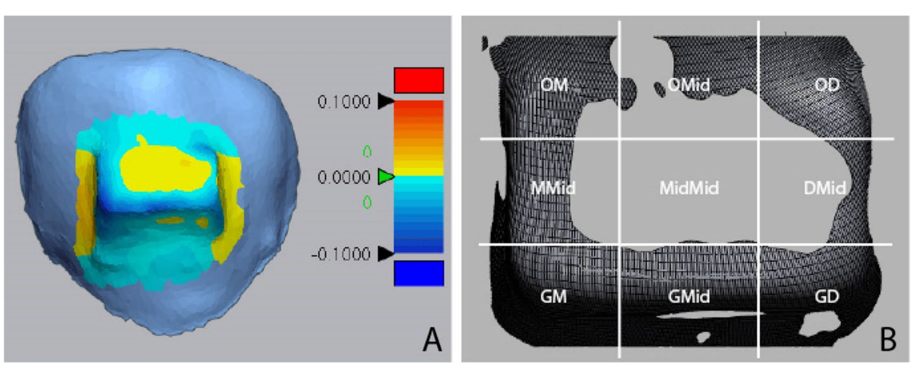

Fig. 3 **A** Superimposition showed morphological differences, the darker the blue color, the greater the wear depth. **B** Boolean subtraction showed wear parts of attachment

Table 2 Means and SDs (mm^3) of wear volume according to attachment area and composite

Area	Composite	Mean	SD	N	Area	Composite	Mean	SD	N	Area	Composite	Mean	SD	N
OM	Tetric	0.0090	0.0077	6	OMid	Tetric	0.0067	0.0091	6	OD	Tetric	0.0088	0.0048	6
	Beautifil	0.0099	0.0064	6		Beautifil	0.0066	0.0074	6		Beautifil	0.0079	0.0051	6
	Z350	0.0075	0.0061	6		Z350	0.0054	0.0064	6		Z350	0.0131	0.0076	6
	Total	0.0088	0.0064	18		Total	0.0062	0.0072	18		Total	0.0099	0.0061	18
MidM	Tetric	0.0134	0.0102	6	MidMid	Tetric	0.0100	0.0103	6	MidD	Tetric	0.0137	0.0070	6
	Beautifil	0.0138	0.0078	6		Beautifil	0.0053	0.0073	6		Beautifil	0.0100	0.0091	6
	Z350	0.0098	0.0086	6		Z350	0.0065	0.0113	6		Z350	0.0150	0.0139	6
	Total	0.0123	0.0086	18		Total	0.0073	0.0094	18		Total	0.0129	0.0100	18
GM	Tetric	0.0152	0.0139	6	GMid	Tetric	0.0125	0.0062	6	GD	Tetric	0.0173	0.0064	6
	Beautifil	0.0297	0.0226	6		Beautifil	0.0248	0.0118	6		Beautifil	0.0222	0.0134	6
	Z350	0.0324	0.0241	6		Z350	0.0313	0.0176	6		Z350	0.0345	0.0130	6
	Total	0.0258	0.0209	18		Total	0.0228	0.0144	18		Total	0.0247	0.0130	18

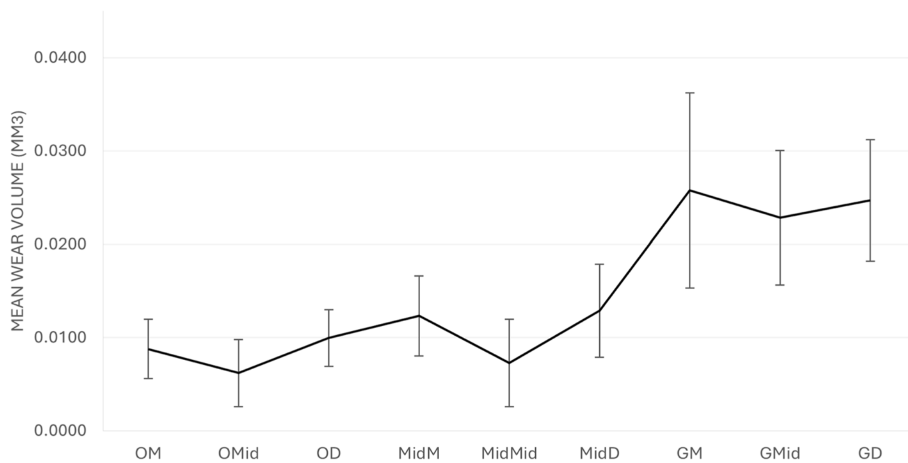

Fig. 4 Comparison of wear volume among attachment areas

retentive force on Days 7, 10, and 14, although the differences were not significant.

Correlation between overall attachment wear volume and retentive force change

Pearson correlation showed that the average retentive force change did not correlate with overall attachment wear volume ($r = -0.491$, $p = 0.179$).

Discussion

This study aimed to evaluate the wear volumes of nanohybrid flowable and nanofilled sculptable resin composites used in clear aligner attachments over a simulated 24-week insertion/removal period, and to investigate the correlation between attachment wear and changes in retentive force. There were no significant differences in attachment wear volumes or clear aligner retentive forces among different resin composite attachments. However, different parts of the attachments showed significant differences in wear volumes. Clear aligner retentive forces were significantly different across various days of aligner insertion and removal. Additionally, there was no correlation between the average change in retentive force and the overall attachment wear volume. The findings provide insights into how different resin composites perform in terms of wear resistance and their impact on aligner retention.

In clear aligner therapy, patients typically wear aligners continuously, removing them only for eating and brushing, which results in approximately three cycles of insertion and removal per day. To simulate this clinical usage, we designed a simulation of 24-week study using twelve aligners, each subjected to 42 insertion/removal cycles over a 14-day period. The wear patterns and retentive forces observed over this simulated period help address key questions about material performance.

Table 3 Means and SDs (N) of retentive force according to day and type of composite

Day	Composite	Mean	SD	N
D1	Tetric	77.8486	2.18997	36
	Beautifil	78.5428	1.81343	36
	Z350	78.4730	3.15985	36
	Total	78.2881	2.45129	108
D2	Tetric	59.2766	2.95292	36
	Beautifil	58.3317	3.62841	36
	Z350	59.2513	3.79733	36
	Total	58.9532	3.47425	108
D7	Tetric	53.4333	2.57521	36
	Beautifil	55.0768	3.98275	36
	Z350	55.2837	4.00522	36
	Total	54.5979	3.64648	108
D10	Tetric	52.6442	2.49815	36
	Beautifil	54.2447	3.91516	36
	Z350	53.9161	3.98475	36
	Total	53.6017	3.56791	108
D14	Tetric	51.7072	2.70136	36
	Beautifil	53.0335	4.16816	36
	Z350	52.7819	4.56981	36
	Total	52.5075	3.90317	108

Attachments bonded to the tooth surface are crucial for facilitating tooth movement and enhancing aligner retention. They must maintain dimensional stability and possess adequate wear resistance throughout treatment. The resin composites selected for this study were chosen for their aesthetic and mechanical properties. Filtek™ Z350XT is one of the recommended attachment materials by Invisalign®, and Tetric N-Flow is suggested for attachment construction by Bouchez (2019) [4]. Additionally, Beautifil Injectable X has been used recently for various restorative applications, for example, restoration of cavities, tooth splinting, and restoration of occlusal wear. These materials also differ in handling properties, with viscosities ranging from highest to lowest, respectively.

As technology advances, the mechanical and physical properties of flowable resin composites have improved, with some showing comparable wear resistance to nanofilled sculptable composites [8, 9]. Chen et al. (2021) evaluated the 2-body wear of resin composite specimens using a 5 mm stainless-steel ball to apply a 30 N load at 2 Hz for 10,000 cycles under water. By measuring mass loss to calculate wear volume, they found that Filtek™ Z350XT flowable exhibited significantly higher wear volume loss compared to Filtek™ Z350XT universal and SonicFill. This was likely due to its lower filler content and more flowable nature, which made it less resistant to mechanical wear [18]. In contrast, our study found no significant difference in wear volumes between nanofilled sculptable (Filtek™ Z350 XT univaersal) and nanohybrid flowable composites (Beautifil Injectable X and Tetric N-Flow), suggesting that those composites exhibit comparable durability under repeated aligner insertion and removal over the 24-week simulation. Different experimental and wear measurement methods could influence the contrasting of the findings. Intraoral scanners have been shown to capture details with high accuracy. The 3Shape Trios3® scanner has a resolution of 41.21 triangle points/ mm^2 [19]. Within the area of interest in our study (approximately 13.5 mm^2 of attachment), this corresponds to more than 500 triangle points used to three-dimensionally measure the tested area. A study investigating small area accuracy, specifically the crown preparation finish line, reported that Trios3®

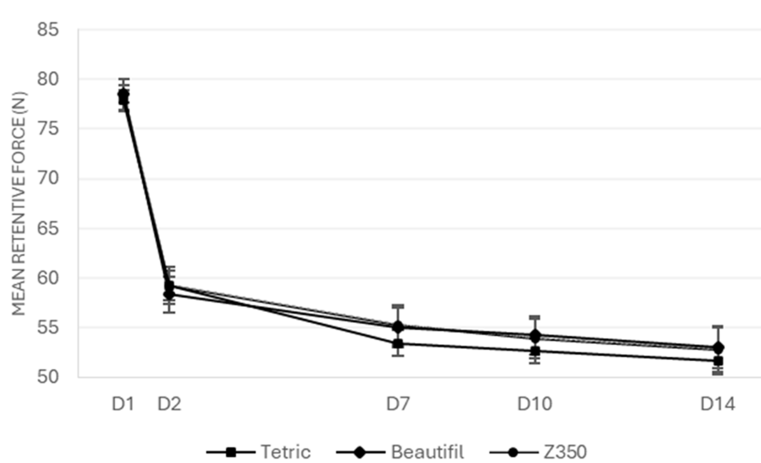

Fig. 5 Retentive force on Days 1, 2, 7, 10, and 14 for different composites

demonstrated high resolution with deviations of less than 25 microns [20]. Consequently, the wear observed in our study was measured within a reasonable level of accuracy.

The highest wear in our study was observed in the gingival regions of the attachments regardless of composite type, due to the concentration of mechanical stress during aligner insertion and removal. This wear pattern aligns with Li and Yang (2024), who reported wear beginning at the edges, particularly at the gingival corners of 3-mm rectangular attachments during an 8-month clear aligner treatment [21]. However, Jardim et al. (2024) observed that after at least 4 months of treatment, the most significant wear occurred on the distal surfaces of conventional attachments [22]. These differences suggest that the wear volume and patterns of attachments are influenced by various factors, including material composition, patient habits, and the specific mechanical forces applied during treatment. In addition, the attachment volume decreased significantly over time, with the greatest wear occurring in the first few months of treatment [21]. Therefore, longer cycles of aligner insertion and removal of aligners could impact attachment integrity.

Both two-body and three-body wear processes are influenced by the characteristics of the abrasive surface and the abrasive particles involved [23, 24]. Our research was conducted in a laboratory setting, simulating a two-body wear situation that may not fully replicate clinical conditions. In real practice, aligner removal typically involves lifting the edge with fingernails over the attachment, potentially resulting in less contact between the aligner and attachment surface than in our setup, where the aligner was pulled perpendicularly to the occlusal plane by a universal testing machine. Additionally, oral environment or intraoral aging can affect the molecular and mechanical properties of the thermoplastic materials used in aligners [25, 26]. Furthermore, cleaning solutions and methods can affect intraoral pH [27] and alter the flexural modulus of materials like Essix ACE [28]. While these variables may lead to reduced attachment wear in clinical scenarios, other factors, such as toothpaste type, toothbrush abrasiveness, brushing techniques, diet, and the intraoral aging of resin composites, could contribute to increased wear. Furthermore, tooth movement forces in clinical practice are actively generated during the active fitting of aligners on teeth and attachments contrasting with our research which involved passive fitting.

Our study observed a significant decrease in the retentive force of each aligner from day 1 to day 2, with a continuous decline over subsequent days, regardless of the resin composite used. This notable drop in retention from the first to second day can be attributed to visible stretching of the aligner in the gingival area adjacent to the attachments, as reported in a preliminary study [16]. Despite wear at the gingival areas of the attachments, there were no significant differences in the retention of twelve consecutive aligners, nor was there any correlation between retentive force changes and wear volume. However, aligner retention can be influenced by various factors, including the number, shape, and position of attachments, as well as the materials, thickness, and design of the aligners themselves [13–15]. Consequently, the retentive force may vary across different clinical scenarios.

To improve future research, increasing the sample size and extending the experimental duration would enhance the generalizability of the findings. Researchers could also explore attachment wear under conditions more closely mimicking clinical scenarios and investigate the impact of different aligner materials on attachment durability. Moreover, studying the effect of attachment wear on the accuracy of tooth movement and conducting in vivo studies could provide more clinically relevant data and deepen our understanding of attachment performance in clear aligner therapy.

Conclusion

Within the scope of this laboratory investigation, following the insertion and removal of 12 aligners over a simulated 24-week period, the gingival areas primarily exhibited significantly higher wear volume than other attachment parts, with no significant difference among two nanohybrid flowable and a nanofilled sculptable resin composites. The retentive force of each aligner decreased significantly from Days 1, 2, 7, 10, to 14, with no significant change in retentive force among the 1st to 12th aligners. Despite the reduction in attachment volume, there was no impact on mean retentive force among aligners over the 24-week period. Nanohybrid flowable (Tetric N-Flow and Beautifil Injectable X) and nanofilled sculptable (Filtek™ Z350 XT) can be used to fabricate attachments with similar wear volume and patterns, and retentive force for clear aligners.

Abbreviations

Bis-GMA	Bisphenol A Glycidyl Methacrylate
UDMA	Urethane Dimethacrylate
TEGDMA	Triethylene Glycol Dimethacrylate
Bis-MPEPP	2,2-Bis[(4-Methacryloxy Polyethoxy) Phenyl] Propane
PEGDMA	Polyethylene Glycol Dimethacrylate
Bis-EMA	Bisphenol A Ethoxylated Dimethacrylate
Tetric	Tetric N-Flow
Beautifil	Beautifil Injectable X
Z350	Filtek™ Z350 XT Universal
D1	Average Retentive Force of Aligners in Day 1
D2	Average Retentive Force of Aligners in Day 2
D7	Average Retentive Force of Aligners in Day 7
D10	Average Retentive Force of Aligners in Day 10
D14	Average Retentive Force of Aligners in Day 14
OM	Occluso-Mesial
OMid	Occluso-Middle
OD	Occluso-Distal

MidM	Middle-Mesial
MidMid	Middle-Middle
MidD	Middle-Distal
GM	Gingival-Mesial
GMid	Gingival-Middle
GD	Gingival-Distal
ANOVA	Analysis of Variance
ICC	Intraclass Correlation Coefficient
SD	Standard Deviation

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Authors' contributions
NR contributed the concept, design, performed all experiments, data acquisition and interpretation, and drafted the manuscript. JC contributed the concept, design, validated the experimental methods, performed statistical analyses and data interpretation, and revised the manuscript. CT substantively performed literature searching, revised and edited the manuscript. All authors have reviewed and approved the final submitted version of the manuscript and agree to be accountable for all aspects of the work, ensuring any questions related to accuracy or integrity are appropriately addressed and resolved in the literature.

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Data availability
The datasets used and/or analyzed during the current study are available from the author on reasonable request.

Declarations

Ethics approval and consent to participate
This study utilized a publicly available model from an open repository, which is anonymized and non-identifiable. As no human subjects were directly involved and no new data were collected, ethical approval was not sought.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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