A novel methodology for assessing, evaluating, and classifying defects in clear aligner attachments

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Attachments are composite resin geometries considered important adjuncts for clear aligner therapy (CAT) effectiveness. They are bonded to the tooth surfaces to improve control during orthodontic tooth movement (OTM). Attachments augment tooth surfaces to facilitate force application to achieve the desired OTM and also to enhance the retention of the aligner. A comprehensive description of CAT attachment morphology, common attachment defects, or a scientific methodology to assess attachment clinical placement and dimensions has not been described. This paper discusses morphologic and geometric features (active surface, passive surface, base, and ridges) of attachments and introduces a classification system for attachment defects (volumetric, abrasion, location, and errors). Finally, a systematic methodology to assess attachment defects is outlined to allow for further research into attachment placement in a clinical setting.
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Introduction

Clear aligner therapy (CAT) was introduced to treat mild to moderate malocclusions. However, the scope of treated malocclusions has broadened as CAT has become a routine orthodontic approach due to advances in thermoplastic materials, digital technology, and patient demand.[1,2] The literature regarding the efficacy of orthodontic tooth movement (OTM) using CAT is growing, and numerous factors that influence the efficacy of OTM using CAT have been identified.[1] These include patient co-operation, aligner thickness and the height of trim lines, treatment staging and aligner change frequency, the amount of interproximal enamel reduction, the use of auxiliary treatment including sectional fixed appliances, temporary anchorage devices (TADs), elastics, altered aligner geometries, and attachments.[1] Associated with these factors, the accuracy of more challenging OTMs, such as overbite correction, torque, and expansion, has been questioned.[2–7]

CAT auxiliaries have been developed to improve treatment effectiveness. These include altered aligner geometries such as pressure points and torquing ridges, occlusal interferences such as bite ramps and bite blocks, methods to attach elastics and attachments. Attachments are composite resin geometries bonded to the tooth surface. Initially patented by Martz in 1988,[8] attachments were reintroduced to modern CAT design by Vaskalic and Boyd in 2001[9] to improve the control of tooth and root movements. Attachments of various designs have been developed and the shape and size have been claimed to improve the clinical effectiveness of CAT.[9,10] Over time, attachment size and shape have continued to evolve with the release of engineered attachments with active surfaces;[11] however, their benefits have been questioned.[12,13]

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Recent systematic reviews on attachments and CAT have concluded that, although the evidence is weak and contradictory for several types of OTM, the use of attachments generally improves both OTM efficacy and aligner retention. Attachment size, geometry, and placement site on the tooth have been shown to influence OTM.[1,14]

Not all tooth surfaces are shaped to receive the necessary forces delivered by CAT in a desirable direction. Particular types of OTM, dental morphology and the limitations of clear aligners often warrant the addition of attachments to enhance the expression of the planned OTM. Attachments provide a surface on which forces can be applied to achieve the required OTM. Attachments should be accurately engaged during CAT to apply the appropriate directional force and move teeth into planned positions, according to the computer-aided design (CAD) treatment plan. Attachment locations and dimensions should be accurate for CAT to effectively move teeth and reflect the CAD plan.[15–17] Errors in attachment bonding, such as adhesive flash, can change the force vectors and result in the application of unpredictable forces.[18]

The role of attachment defects, position, and geometry and their effect on the efficacy of OTM using CAT has yet to be investigated in a clinical setting, and only a limited number of in vitro investigations have been published. Where available, the literature has focused on individual complications associated with the use of attachments, such as adhesive flash,[18] while other aspects of attachment geometry and accuracy have not been investigated.

The present paper aims to outline the features of CAT attachments, propose an attachment defect classification, and describe a method to assess attachments in vivo. Once described, this method can be used for further research to establish the accuracy and efficacy of attachments and their role in orthodontic CAT.

Methodology

To assess the accuracy and precision of CAT attachments, patients' dentitions were intra-orally scanned to produce a 3D stereolithography (STL) file at different time points. The inaccuracies of attachments may be analysed by superimposing the ideal tooth and attachment shape (according to the CAD plan) with the achieved attachment position and geometry at different time points: the initial timepoint (T0) before placement of attachments; following placement of attachments (T1); and the ideal attachment shapes (T1A) from the CAT manufacturer.

Any intra-oral scanner with sufficient accuracy and precision for a CAD orthodontic plan can be used to obtain an STL file for the T0 scan. A calibrated Medit i700 scanner (Medit, Seoul, Republic of Korea) in HD mode was used for the current investigation. It had an independently tested mean and median accuracy of 6 μm[19] and a company claimed accuracy of 11μm. The T1 intra-oral scan was completed using the same scanner and settings to assess the accuracy of attachment placement.

The T1A STL tooth crowns were segmented, individually aligned, and superimposed over the T1 STL file. Segmentation techniques vary depending on the STL file provided by the manufacturer. Flood fill and manual checking of the highlighted area and gingival margins are indicated for single-shell STL file segmentation using Medit Design (Medit, Seoul, Republic of Korea). Multi-shell STL files, in which each tooth and associated gingiva is a distinct shell, can be saved separately using Meshmixer (Autodesk, San Rafael, California, United States of America). Multi-shell STL files are preferred for accuracy as this method has no potential to alter the shape at the margins. Once aligned to T1, the T1A models are duplicated to digitally remove the surrounding tooth from one model, leaving only the aligned attachments for volumetric comparison. Once aligned, the T1A model remains unchanged for overall and linear assessments. The STL files were exported to Geomagic Control X metrology software (version 2017.0.3; 3D systems, Rock Hill, SC, USA) to allow assessment of the accuracy of attachment placement and morphology. Geomagic Control X remains the gold standard for dental research and accuracy in meteorological software.[20,21]

Results

Subtle dental movements were observed between the initial scanning (T0) and the placement of the attachments (T1). The small movements may be due to intra-oral scanning errors, minor dental movement, changes in dental position due to occlusal load or pressure from the application of the attachment template or the thixotropic nature of

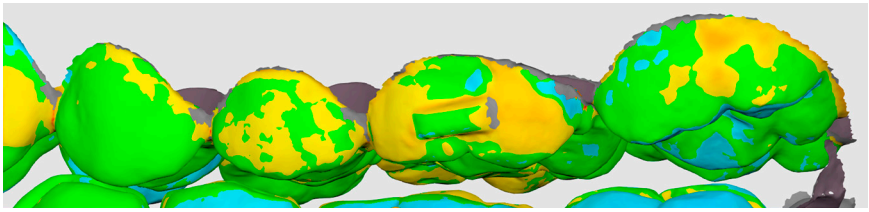


Figure 1. There are mild discrepancies (yellow = 0.1–0.3mm) in tooth shape when T0 is aligned with T1. As these teeth are aligned individually, this discrepancy can be attributed to scanning errors or changes in the tooth's shape. Due to the location and clinical feedback, this change in shape was attributed to the scanner detecting different volumes of dental plaque between T0 and T1.

the periodontal membrane.[22] Changes in systemic blood pressure can also create slight differences in the position of teeth.[23] By comparing scans at T0 and T1, and assessing teeth that did not have attachments placed, this methodology could also detect small changes in tooth shape due to the presence or absence of plaque (Figure 1). The changes were localised to areas where plaque was detected and were greater than the 6 to 11µm discrepancy expected using the i-700 intra-oral scanner. It is important to note that, although expected,[21] minor changes between scans should be minimised or accounted for in the methodology through segmentation and alignment, as described below.

Due to the small dental movements, minor discrepancies on all tooth surfaces were observed when T0 was compared to T1 using whole arch best-fit alignment (Figure 2A). These discrepancies are not representative of the clinical accuracy of attachment placement but of the small, expected movements. This is shown in Figure 2B, in which a cross-section was taken through the upper right central incisor on an entire arch best-fit aligned model. The cross-section clearly shows discrepancies across the crown of the upper right central incisor, which are not representative of the clinical accuracy of the attachment but reflect minor dental changes between T0 and T1.

The minor tooth movement that is routinely observed created the need to align the teeth from T1 to T1A using the individual dental crowns to a best-fit model for accurate assessment of the attachment discrepancies. Figure 2C shows the same upper right central incisor in cross-section at T1, individually aligned with T1A. The tooth crown shows nearly perfect alignment between T1 and T1A, except where the attachment was placed. The arch discrepancies created from an overall alignment using best-fit followed by comparison can be seen in Figure 2A. In contrast, Figure 2D shows the upper right canine individually aligned to the best fit, resulting in this tooth being ideally aligned; however, the rest of the arch is dramatically out of line due to the multiplication of this error across the arch.

Segmenting the T1A STL tooth crowns, individually aligning, and superimposition over the T1 STL file removes the errors from dental movements and aligner changes. It also eliminates the need for a passive T1A STL to be made available by the CAT manufacturer, as the attachments can be assessed against any CAD STL file when using segmentation, as movement is accounted for in the methodology. This allows for a detailed assessment so that any differences detected are likely to indicate a difference in the clinical shape of the attachment compared to the planned CAD attachment shape. It is important to note that all teeth on the T1A model must be individually aligned to T1 to eliminate these errors. Following the superimposition of the segmented T1A teeth as described, various problems with attachment geometry and placement were identified and categorised in Table I and illustrated in Figure 3.

Discussion

The treating clinician can place CAT attachments on any tooth surface. The attachment's potential size, vertical and horizontal position or rotational orientation is infinite but can be divided into four fundamental morphologies. Attachments may be described based on their shape as ellipsoidal, rectangular, bevelled (triangular), or pyramidal (Figure 4). These shapes can be further divided or modified to achieve the desired active surface for force application. For example, trimming an ellipsoid attachment provides one ridge and a flat, active face designed for OTM in one direction (Figure 5) but will perform poorly in another direction.[24]

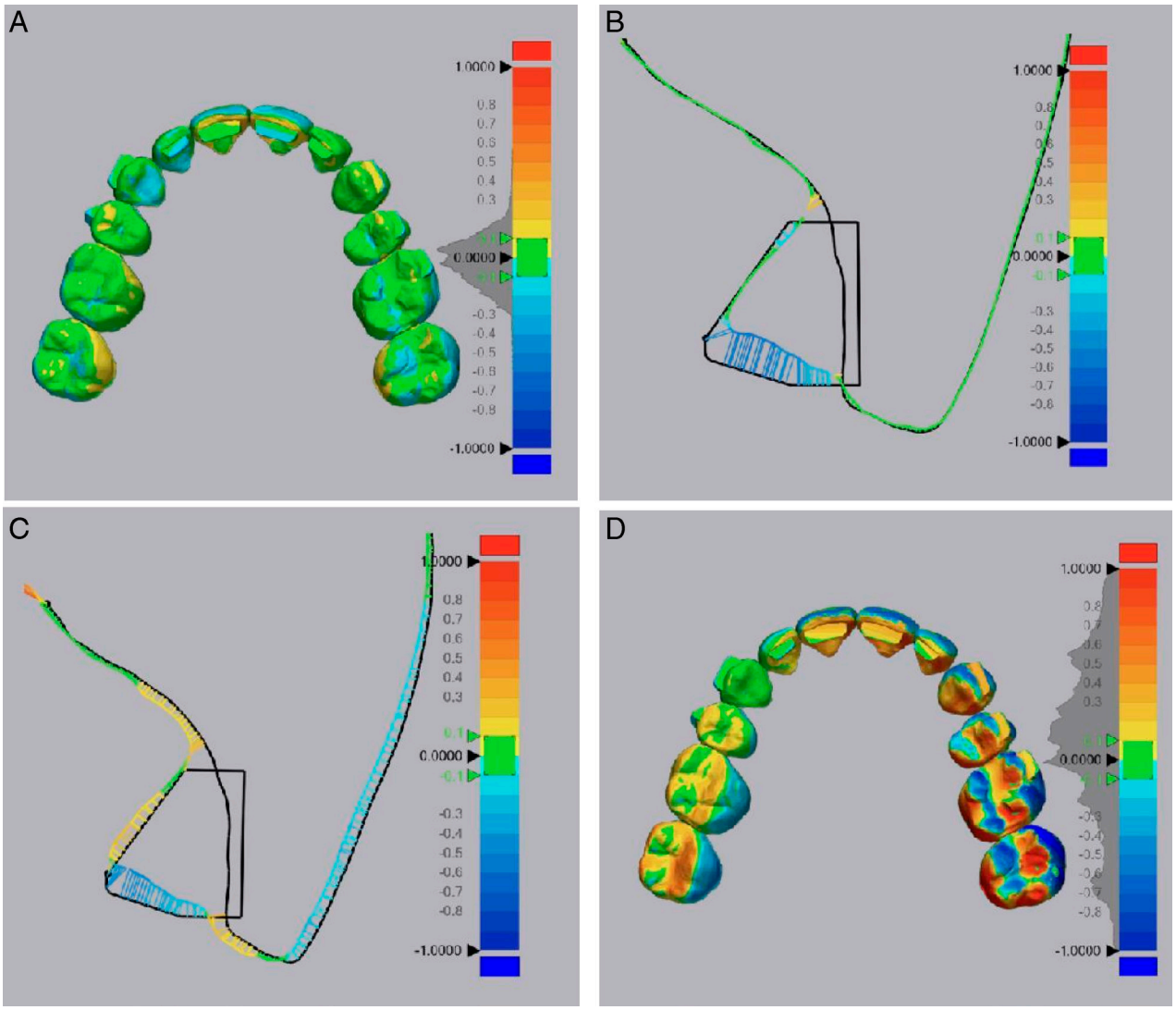


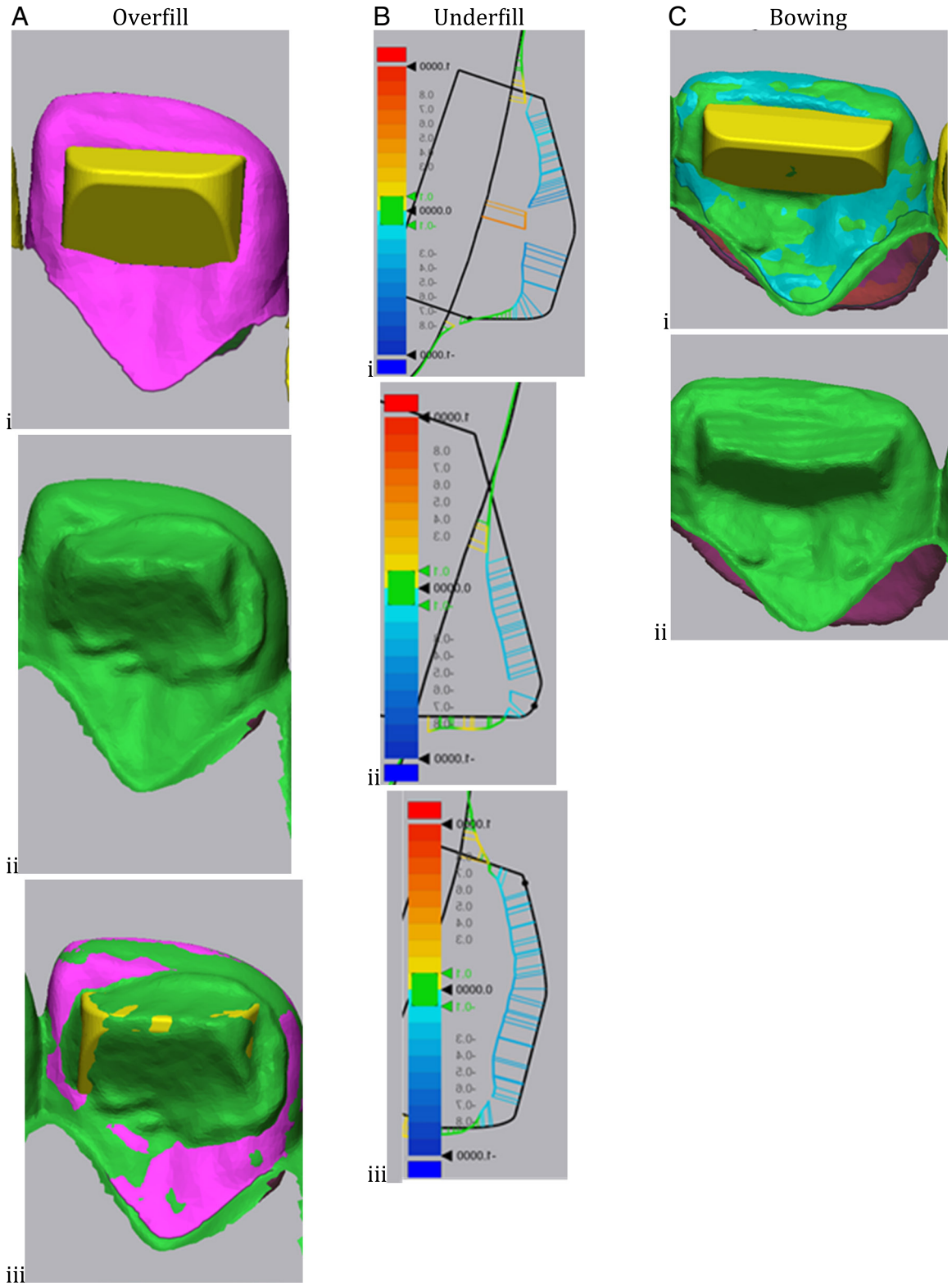
Figure 2. A, Occlusal image of maxillary arch aligned to best fit showing discrepancies on unaffected surfaces attributed to small dental movements. B, A linear section through the upper right central incisor, with the upper right central incisor individually aligned to best fit. There is reasonable alignment across the whole crown, with significant discrepancies related only to the attachment. C, The same section through the upper right central incisor as in Figure 2B; however, this section shows the discrepancies across the crown and attachment surfaces. D, The occlusal image of the maxillary arch aligned to a single tooth (upper right canine) shows an ideal fit for this tooth but significant discrepancies on all other teeth.

Attachments can be further modified by trimming or smoothing the attachment ridges.

The four elements of attachment design can be described as an active surface, a passive surface, a base, and ridges (Figure 6). The active surface of an attachment is the area intended to contact the CAT plastic. Along with the tooth surface, the active surface of an attachment is where the force vectors to achieve OTM and retain the aligner are applied (Figure 6A). The passive surface of an attachment describes the remaining attachment portion, where the CAT is not intended to directly apply forces. The passive surface provides structural rigidity for the attachment, resistance to oral forces, and sufficient volume for the aligner to engage with the active surface and dissipate the force to the tooth without interfering with the aligner fit (Figure 6B). The attachment's ridges form sharp angles between the active and passive surfaces. The ridges give the attachment its overall shape and mark clear boundaries between the active and passive surfaces, thereby maximising the active surface's engagement with the aligner. An ellipsoid attachment has no ridges due to its smooth surface, and hemi-ellipsoid

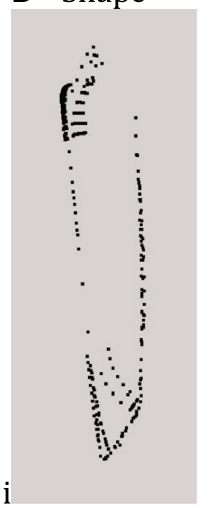
Table I. Common attachment defects classification

	Defects that fundamentally change the attachment size.	
	Overfill	Excess composite resin associated directly with the attachments' surfaces results in an attachment that is larger volumetrically than planned. The overall shape of the attachment can be accurate; however, excess resin in the template causes the attachment to protrude further than intended (Figure 3A)
	Underfill	A deficiency in the composite resin results in decreased attachment volume and smaller surfaces than planned. However, the overall shape of the attachment remains intact (Figure 3B)
Volumetric	Bowing	A discrepancy that results in one or more attachment surfaces being distorted towards the centre of the attachment ridges, creating a bowed appearance. This is most likely attributed to distortion within the attachment template because of pressure on this more flexible part of the template (Figure 3C)
	Shape	Attachments with a significant volumetric error so that the ridges are not accurately reproduced, resulting in a defect in the overall shape (Figure 3D)
	Separation	The shape of the attachment ridges and the active and passive faces are intact; however, there is a substantial volumetric defect at the base of the attachment between the attachment and the tooth (Figure 3E)
Abrasion	Abrasion is the gradual loss or distortion of an attachment due to mechanical and/or chemical interactions. Attachments exist in the oral environment; abrasion of attachments occurs through normal oral functions and repeated removal and replacement of aligners. (Figure 3F)	
Locational	Defects due to the attachment being bonded in a position other than what was planned (Figure 3G)	
Errors	Defects in attachments that do not fit into one of the other categories	
	Bubbles	There is a minor round volumetric error at the surface of the attachments (Figure 3H)
	Porosities	Bubbles in the composite resin that are contained within the body of the attachment. These may not affect the overall dimensions of the attachment; however, they may affect its structural integrity and the aesthetics of the attachment (Figure 3I)
	Roughness	Increased surface roughness when compared to the ideal CAD-CAM design due to the attachment template being formed on a coarse 3D printed model (Figure 3J)
	Flash	A thin layer of excess composite around the perimeter of the attachment, which does not affect the attachment volume but may compromise the accuracy of the location of the attachment (Figure 3K)
	Bonding	Failure of the bonding of the attachment to the tooth (Figure 3L)


A
Overfill
i
ii
iii
B
Underfill
i
ii
iii
C
Bowing
i
ii

D Shape

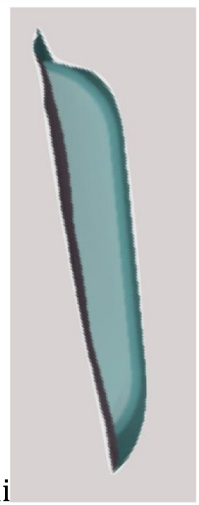
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iii

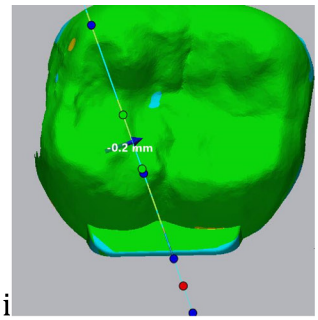


E Seperation



F Abrasion

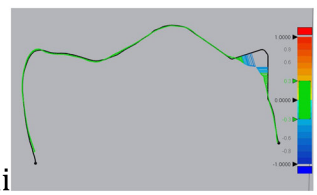
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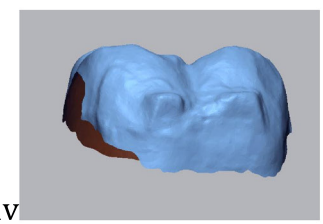
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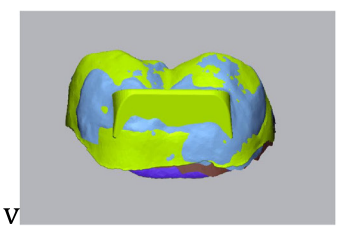
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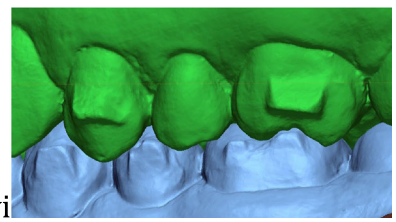
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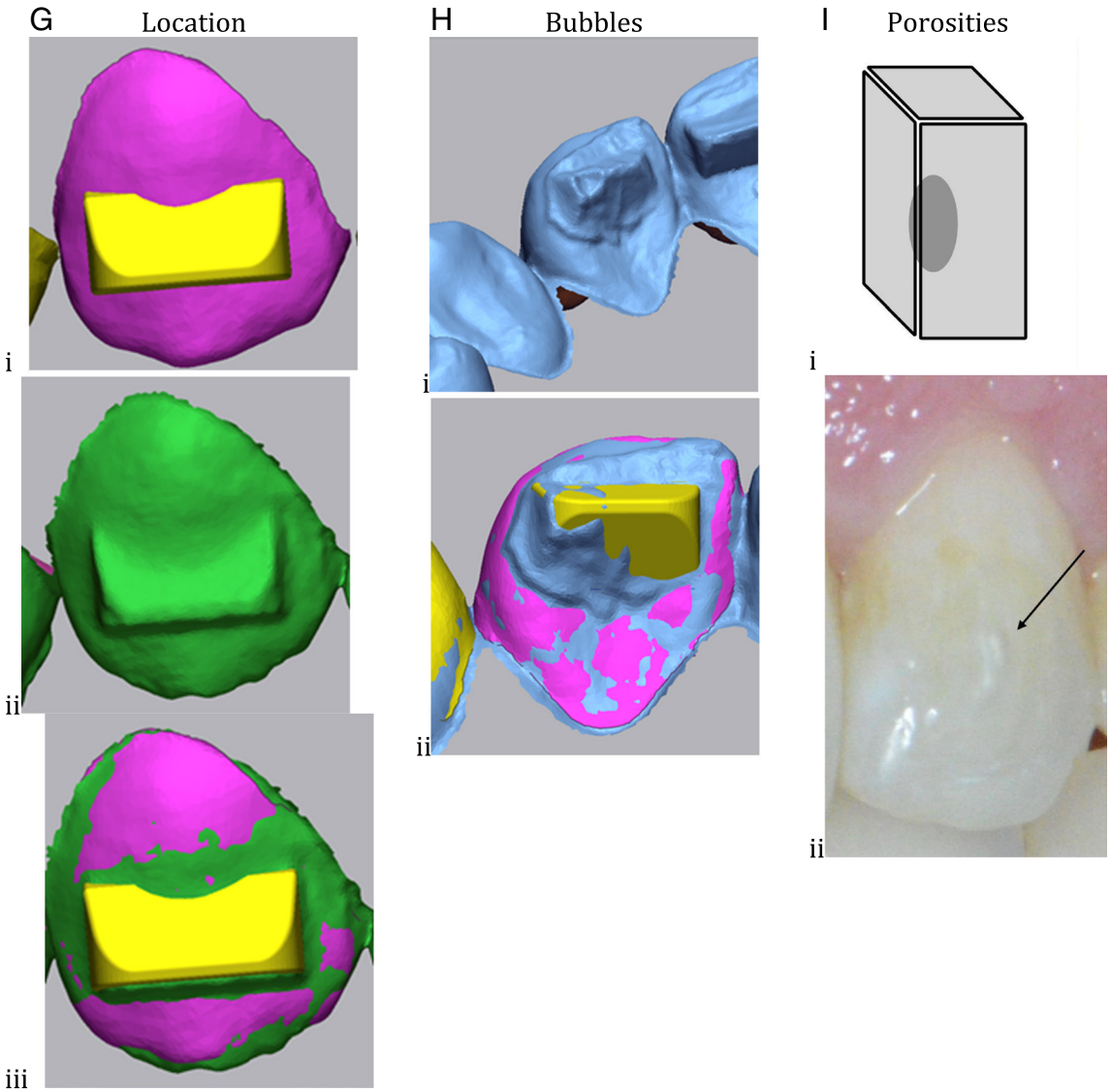


v



vi





attachments only have one ridge (Figure 6C). The base is where the attachment adheres to the tooth crown (Figure 6D).

The literature discusses the need for bonding precision and means for assessing forces using finite element analysis and bench studies.[15,16,18,24,25] However, these in vitro experiments use ideal attachment shapes engaging with the aligner that do not represent the clinical realities. The present study classifies common attachment defects as volumetric, abrasion, location, and other errors. An attachment may have one or more defects, as described in Table I and illustrated in Figure 3.

Scanning and comparing attachments at multiple time points can be used to assess their stability and efficacy. A retrospective analysis of OTMs on teeth with attachments based on their precision relative to their intended shape and position is feasible. This methodology can be used to assess the volumetric loss of attachment surfaces due to physical and chemical abrasion of the attachment. However, factors such as attachment abrasion and debonded attachments will confound retrospective studies which attempt to assess the accuracy of attachments and CAT outcomes.

Once baseline data is obtained, as described for the present study, subsequent scans at different time points (T2 and onwards) can assess materials, long-term follow-up of bonding techniques, or a relationship between attachment defects and OTM. Using the same methodology for comparison with

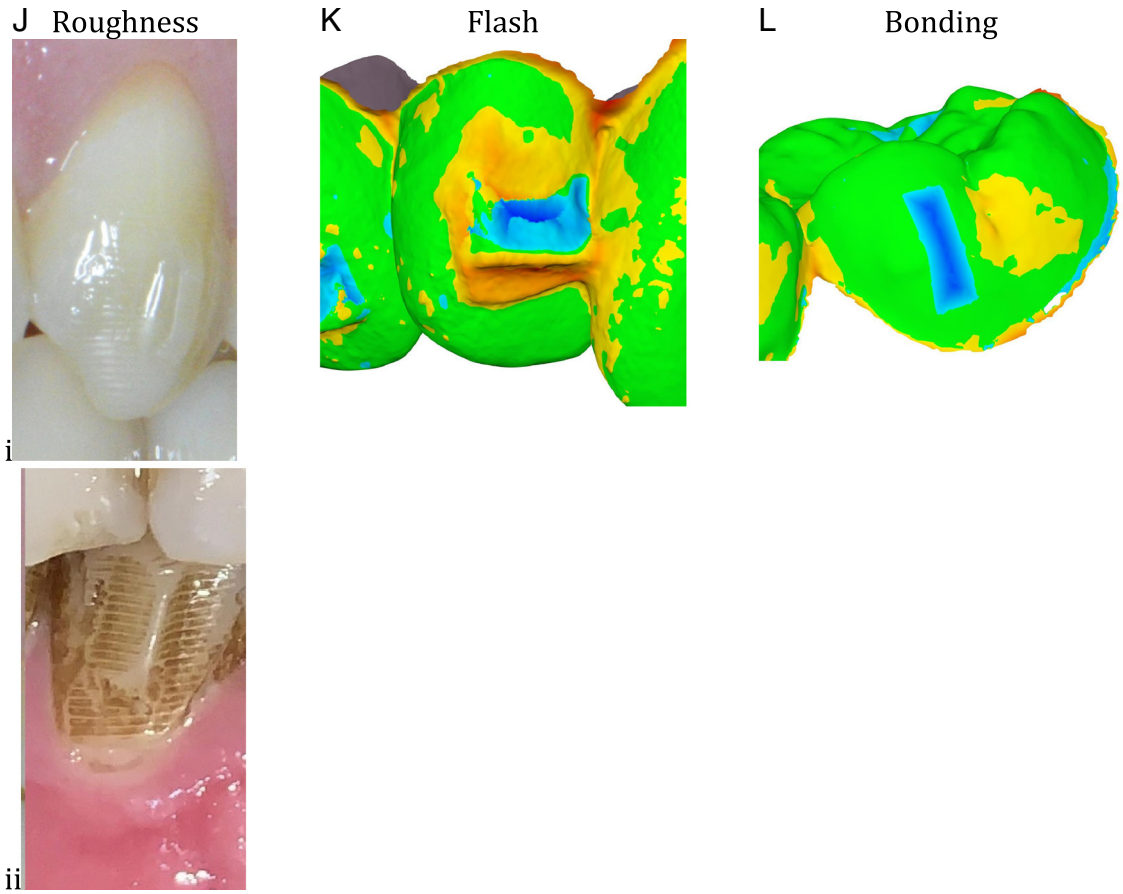


Figure 3. A, Attachment overfill error. (i) shows the ideal attachment, and (ii) shows the placed attachment. (iii) superimposes these two to demonstrate the degree of error. B, Resin underfill demonstrated with three 2D slices, with the ideal attachment outline in black and the actual attachment deficit highlighted with coloured lines. C, Two images demonstrating the ideal attachment (i) and the actual attachment (ii). Bowing in the middle third is observed due to occlusal pressure distorting the attachment template during curing. D, Three images showing no definable attachment ridges when only the accurate points are displayed (i) resulting in an attachment shape (ii) being unrecognisable from the planned attachment (iii). E, While the faces and ridges of the attachment appear to be intact, there is a partial separation of the attachment from the tooth surface at the base. This is attributed to underfilling the attachment template in one section so that although the attachment bonds to the tooth, the base is not circumferentially intact. F, Abrasion is shown on a 36 (iv). The accuracy of the initial attachment is shown (i) compared to the attachment after 11 months of treatment (ii-v). The abrasion appears to be due to occlusal load on a specific portion of the 36 attachment (vi). Similar changes are observed on the 35, and flash is visible on the mesial aspect of the 36. G, A series of images shows an ideally shaped and volumetrically accurate attachment (ii-iii) placed more incisal than the planned attachment (i). H, An image showing a surface bubble (i) and comparison with the ideal (ii); this image also demonstrates overfill and flash. I, A model (i) and image (ii) with an arrow identifying a porosity inside an attachment. J, Surface roughness of a new attachment (i) and old attachment (ii) attributed to the surface roughness of the template being replicated in the attachment. K, Flash is demonstrated in yellow surrounding the underfilled (blue) attachment and aligned (green) tooth. L, A debonded or missing attachment is noted as a blue rectangle on the otherwise aligned (green) tooth. This tooth also has a yellow area; this difference between T0 and T1 is attributed to dental plaque.

the initial placement (T1) would allow for the assessment of attachment abrasion (Figure 3F). For CAT effectiveness related to the initial attachment accuracy, attachment errors documented between T1 and T1A could then be followed up to determine if more significant discrepancies or specific defects result in changes to CAT effectiveness.

The advent of custom-prefabricated 3D-printed attachments[26] necessitates a description of attachment errors and a method to assess attachments (errors, accuracy, and precision). As custom prefabricated 3D printed attachments are produced to the CAD specifications, the number and severity of errors and volumetric defects are expected to be minimal. However, 3D printing surface characteristics have not been independently assessed, and as the custom-prefabricated 3D-printed attachments are clinically bonded, concerns about locational defects and bonding errors remain. This methodology to analyse attachments can provide a scientific basis for assessing new CAT attachment innovations, materials, or attachment templates. Furthermore, any new method to bond CAT attachments must be evaluated to determine if there is a clinical benefit.

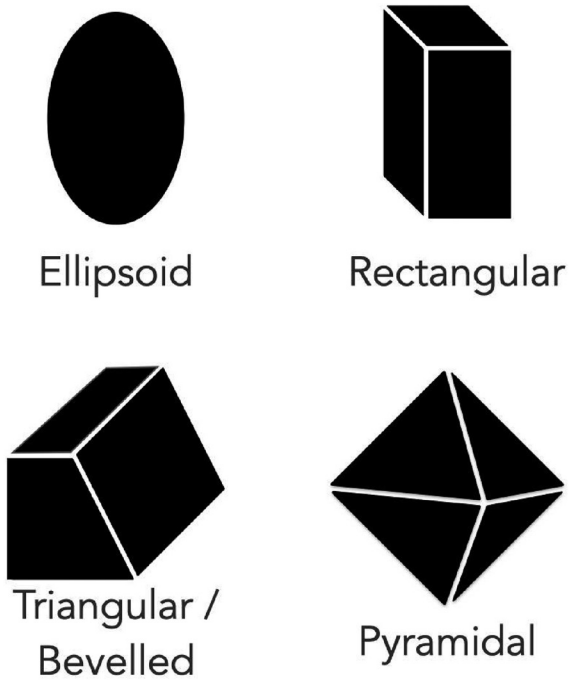


Figure 4. Fundamental attachment morphologies.

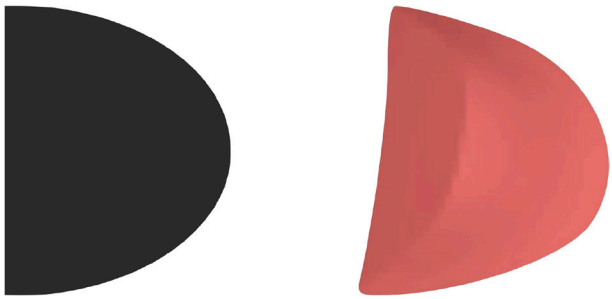


Figure 5. Hemi-Ellipsoid attachment trimmed from an ellipsoid attachmen.

Conclusion

A comprehensive description of attachments, a classification of attachment defects and a method to assess the accuracy of attachments has been overdue. The described methodology allows for the definitions of attachment defects to be established. Defects can then be assessed to determine their impact on CAT OTM. This methodology describes a strategy to collect and analyse data that opens a new area of CAT research to evaluate the accuracy of attachment placement and the effectiveness of different attachment shapes and locations. Once initial data is obtained, scans at multiple time points (T2 and onwards) would allow assessment of attachment integrity throughout treatment and thereby determine the effect of changes due to abrasion or attachment debonding have on the efficacy of planned OTMs. The methodology and analysis can compare and assess in vivo attachment placement methods and materials in the short and long term. This will allow the assessment of composite resins,

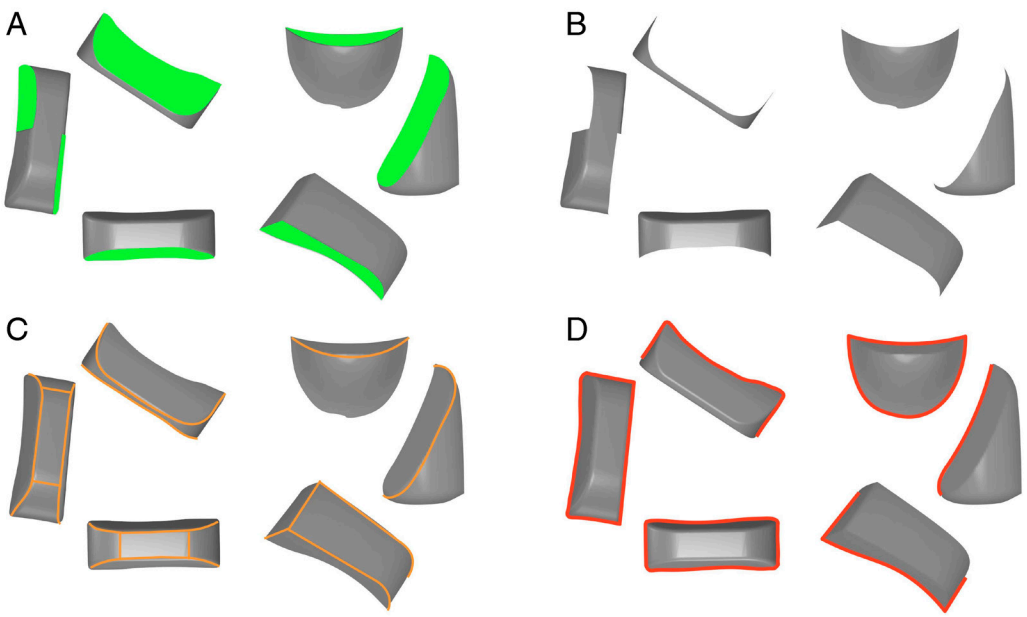


Figure 6. A, The attachment Active Surface(s) (Green) is where force is applied. B, The attachment Passive Surface(s) (Grey). C, The attachment Ridges (Orange) divide the faces of the attachment and define the shape. D, The attachment Base (Red) bonds the attachment to the tooth.

attachment templates, techniques and materials. The results of such an analysis and the identification of common errors may facilitate the development of improved clinical attachment bonding techniques plus materials and lead to more efficient CAT.

Conflict of interest

The authors declare that there is no conflict of interest.

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References

1. Jedliński M, Mazur M, Greco M, Belfus J, Grocholewicz K, Janiszewska-Olszowska J. Attachments for the orthodontic aligner treatment—state of the art—a comprehensive systematic review. Int J Environ Res Public Health. 2023;20:4481.
2. Blundell HL, Weir T, Kerr B, Freer E. Predictability of overbite control with the Invisalign appliance. Am J Orthod Dentofacial Orthop. 2021;160:725–31.
3. Blundell HL, Weir T, Byrne G. Predictability of anterior open bite treatment with Invisalign. Am J Orthod Dentofacial Orthop. 2023;164:674–81.
4. Gaddam R, Freer E, Kerr B, Weir T. Reliability of torque expression by the Invisalign appliance: a retrospective study. Australas Orthod J. 2021;37:3–13.
5. Goh S, Dreyer C, Weir T. The predictability of the mandibular curve of Wilson, buccolingual crown inclination, and transverse expansion expression with Invisalign treatment. Am J Orthod Dentofacial Orthop. 2023;163:109–6.
6. Alwafi A, Bichu YM, Avanessian A, Adel SM, Vaid NR, Zou B. Overview of systematic reviews and meta-analyses assessing the predictability and clinical effectiveness of clear aligner therapy. Dent Rev. 2023;3:100074.
7. Yassir YA, Nabbat SA, McIntyre GT, Bearn DR. Clinical effectiveness of clear aligner treatment compared to fixed appliance treatment: an overview of systematic reviews. Clin Oral Investig. 2022;26:2353–70.
8. Martz MG. Removable tooth positioning appliance and method. U.S. Patent No. 4,793,803. Washington, DC: U.S. Patent and Trademark Office; 1988.
9. Vlaskalic V, Boyd R. Orthodontic treatment of a mildly crowded malocclusion using the Invisalign System. Australas Orthod J. 2001;17:41–6.
10. Vlaskalic V, Boyd RL. Clinical evolution of the Invisalign appliance. J Calif Dent Assoc. 2002;30:769–5.
11. Stacy S, Henderson SM. New innovations represent significant leap forward in clear aligner therapy [Internet]. SAN JOSE, Calif: Align Technolog. https://investor.aligntech.com/static-files/e617b34e-4302-4175-9538-df2a11d2099f
12. Castroflorio T, Sedran A, Parrini S, Garino F, Reverdito M, Capuozzo R, et al. Correction to: Predictability of orthodontic tooth movement with aligners: effect of treatment design. Prog Orthod. 2023;24:47.
13. Groody JT, Lindauer SJ, Kravitz ND, Carrico CK, Madurantakam P, Shroff B, et al. Effect of clear aligner attachment design on extrusion of maxillary lateral incisors: a multicenter, single-blind randomized clinical trial. Am J Orthod Dentofacial Orthop. 2023;164:618–27.
14. Nucera R, Dolci C, Bellocchio AM, Costa S, Barbera S, Rustico L, et al. Effects of composite attachments on orthodontic clear aligners therapy: a systematic review. Materials. 2022;15:533.
15. Weckmann J, Scharf S, Graf I, Schwarze J, Keilig L, Bourauel C, et al. Influence of attachment bonding protocol on precision of the attachment in aligner treatments. J Orofac Orthop Fortschritte Kieferorthopadie Organofficial J Dtsch Ges Kieferorthopadie. 2020;81:30–40.
16. Salmeri F, Barberi E, Lipari F, Nicita F. A novel quality assessment method for the clinical reproduction of orthodontic attachments based on differential entropy. Eng Proc. 2023;56:15.
17. Mantovani E, Castroflorio E, Rossini G, Garino F, Cugliari G, Deregibus A, et al. Scanning electron microscopy analysis of aligner fitting on anchorage attachments. J Orofac Orthop. 2019;80:79–87.
18. Larson ZA. The effect of attachment flash on clear aligner force delivery. 2022
19. Ciocan LT, Vasilescu VG, Răuță SA, Pantea M, Pițuru SM, Imre M. Comparative analysis of four different intraoral scanners: an in vitro study. Diagnostics. 2024;14:13.
20. Adel SM, Vaid NR, El-Harouni N, Kassem H, Zaher AR. Digital model superimpositions: are different software algorithms equally accurate in quantifying linear tooth movements? BMC Oral Health. 2022;22:103.
21. Meade MJ, Weir T, Byrne G. Comparison of digital study model superimposition methods using implant-supported crowns and best-fit algorithms. Am J Orthod Dentofacial Orthop. 2024;166:384–92.e2.
22. Kardos TB, Simpson LO. A new periodontal membrane biology based upon thixotropic concepts. Am J Orthod. 1980;77:508–15.
23. Ioi H, Nakata S, Nakasima A, Counts AL, Nanda RS. Changes in tooth position in humans in relation to arterial blood pressure. Arch Oral Biol. 2002;47:219–26.
24. Ferlias N, Dalstra M, Cornelis MA, Cattaneo PM. In vitro comparison of different Invisalign® and 3Shape® attachment shapes to control premolar rotation. Front Bioeng Biotechnol. 2022;10:840622.
25. Feinberg KB. Translucency, stain resistance and hardness of composites used for invisalign attachments. 2015
26. Pre-formed attachments from clarity aligners [Internet]. 3M; [cited 2024 Aug 26]. https://engage.3m.com/GetAGrip