The effect of variation in orthodontic bracket pad design on shear bond strength, adhesive thickness, tooth adaptation, and curing light penetration

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ABSTRACT

Objectives: To investigate the effect variation in orthodontic bracket pad design has on the shear bond strength, adhesive thickness, bracket-tooth adaptation, and curing light penetration.

Materials and Methods: Three types of bracket pads were compared, a new bracket (NB) pad design (Ortho Classic Corporation, McMinnville, OR), a foil mesh (FM; Victory Series Low Profile, 3M Unitek, Monrovia, CA), and a milled mesh equivalent (MM; BioMimm, Ortho Classic Corporation, McMinnville, OR). The Transbond XT adhesive system and Ortholux LED curing unit were used to bond the brackets to teeth. Forty five brackets, bonded to extracted human maxillary and mandibular premolars, were subjected to a shear bond strength test using a universal testing machine (Qtest, MTS Systems Corporation, Cary, North Carolina). The bond strengths and mode of failure using the Adhesive Remnant Index (ARI) were compared between groups. Fifteen brackets were bonded to a single non-etched extracted human maxillary premolar utilizing a centering device and debonded with the adhesive left intact under the bracket. Brackets were cut in cross-sections and the thickness of the adhesive was measured in multiple locations. A mean overall thickness of adhesive was determined and compared between the three groups. Transmission Fourier-Transform Infrared Spectrometry (FTIR) was performed using an FTIR microscope in near-IR mode at the edge and center of the brackets on the sectioned samples. From the spectroscopy, the area under the carbon double bond (C=C) peaks was measured and compared within the three groups. A one-way analysis of variance (ANOVA) with follow up Tukey Post-hoc testing, a chi-squared test, t-test, and a paired t-test were performed to determine if there were any significant differences.

Results: The mean shear bond strength was 12.22 $\pm$ 2.97 MPa for the NB, 14.74 $\pm$ 4.24 for the FM, and 14.43 $\pm$ 3.58 for the MM. A one-way ANOVA indicated no significant differences (p=0.129). The ARI comparisons indicated that all three pads had similar bracket failure modes and were not significantly

different (x^2=0.600, p=0.741). The mean overall adhesive thickness along the gingival and occlusal pad edges was significantly less in the FM group, 0.089mm, compared to the MM, 0.168mm, and NB, 0.138mm, groups (p<.001). The NB retentive features produced a significantly thicker layer of resin under the bracket pad, 0.434mm, compared to the other two groups and the NB and MM pad designs had retentive features that were significantly closer in proximity to the tooth, 0.014mm and 0.022mm, respectively, than the FM bracket, 0.072mm (P<0.001). All three groups were adapted evenly to the tooth in the mesial-distal direction along the occlusal and gingival edges. The FM and MM groups had significantly more adhesive along the occlusal edge than the gingival (P<0.006), whereas, the NB showed no significant difference in the adhesive thickness at the occlusal and gingival (P=0.08). The conversion of C=C was lower at the edge compared to the center for the FM pad (p=0.012) and higher at the center than at the edge for the MM pad (p=0.016). The conversion of C=C was similar at the NB pad edge and center (p=.856).

Conclusions: Bracket pad design significantly influenced the thickness of adhesive resin, pad adaptation, and curing light penetration. However, these significant differences did not appear to affect the bracket pad's overall bond strength or primary mode of bond failure. Light penetration under the bracket pad was sufficient in all three designs.

INTRODUCTION

Bond failure has been a problem complicating orthodontic treatment and progress since the introduction of bonding materials to dentistry by Buonocore in 1955. Bond failure of orthodontic brackets can be inconvenient to both patients and orthodontists. An increase in bond failure results in compromised treatment efficiency due to an increase in the number of appointments, longer chair time, and/or relapse in tooth movement. Bond failure also influences the patient's perception of the quality of treatment and often results in patient discomfort and the inconvenience of an unplanned orthodontic visit. Sondhi (2000) has estimated that a bond failure can cost a clinician $70 to $200 in overhead depending on the amount of tooth relapse that occurs. Various bonding methods and protocols have been developed to minimize bond failures, yet clinicians and researchers still find a significant rate of failures during orthodontic treatment. In vivo bond failure rates have been reported widely in the literature, ranging from 4% for canines, 5% for incisors, and 9% for premolars (Millet et al, 1998). A median bond failure rate of 5% was reported by orthodontic practitioners in the US through a study questionnaire (Keim et al, 2008).

During active orthodontic treatment, the bond strength between the bracket and the tooth surface must not only be sufficient to allow for the delivery of the orthodontic forces and withstand masticatory loads, but must also be low enough to allow for easy bracket removal. It has been suggested that a bond strength of 6-8MPa is clinically acceptable for orthodontic bonding (Reynolds, 1975). This suggestion was most likely made as a requirement to withstand the forces necessary to produce orthodontic tooth movement under normal mechanotherapy and occlusal loading. Eliades and Bourauel (2005) believe this proposed value does not take into account the stresses developed during the mastication of hard foods or higher chewing velocities, nor does it take into account the aging of the polymeric adhesive and associated environmental stress fatigue phenomenon. Fields et al (1986) studied vertical occlusal forces in children, adolescents, and adults and reported a range of average chewing forces to be 7 to 16 kg and maximum biting forces to be double that at 15 to 30 kg. An 11 mm^2 bracket would require bond strengths of 13.37 to 26.74 MPas to withstand the maximum biting forces reported by Fields et al (2006). This suggests that the bond strength recommended by Reynolds is not enough to withstand maximum biting forces subjected to the brackets throughout orthodontic treatment. Even though Reynolds' bond strength recommendation has been met by various bracket pad designs in the past, the prevalence of bond failure makes bracket bond strength improvements an area of interest by researchers, manufacturers, and clinicians.

Advancements in orthodontic adhesives and bracket pad fabrication has led to a number of options for the clinician and it has been reported that certain combinations perform optimally (Knox et al, 2000; Reimann et al, 2012). Properties of the adhesive, such as viscosity, can influence the adhesive's penetration into the pad's retentive features prior to polymerization. Better penetration enhances the interlocking mechanical retention of the pad, and minimizes voids that may lead to leakage, decalcification, and an oxygen inhibition area of uncured resin (Maijer and Smith, 1981). It has been shown that some pad designs allow for better adhesive penetration than others (Odegaard and Segner, 1988; Regan and van Noort, 1989; Smith and Reynolds, 1991, Knox et al, 2000).

The development of the straight-wire appliance has stressed the importance of accurate bracket placement. An accurate bracket adaptation to the tooth will allow the pre-adjusted appliance to properly express the prescription of the bracket slot. Moreover, a minimal and uniform layer of adhesive maximizes bond strengths (Zachrisson and Brobakken, 1978). It also reduces the inherent bending moment that the bracket/adhesive system is subjected to during heavy masticatory forces that may play a role in the overall bond survival.

Bracket bond strength is also dependent on the polymerization of the adhesive under the metal bracket and this depends on the ability of the light to penetrate the material, as well as, the amount of light scattered from the background surfaces (Fan, 1984). The bracket pad design may influence this light scattering. While studies have used FTIR spectroscopy to evaluate the extent of cure of the adhesive resin under the bracket (Shinya et al, 2009), they have not done so using the normal clinical geometry of a bracket bonded to a natural tooth. Thus, the conversion of orthodontic resin adhesive at the edge of the bracket nearest to the light source compared to the center of the bracket has not been studied.

The aim of the study was to compare the effect of variation in orthodontic bracket pad design on the shear bond strength, the location of bond failure, the adhesive thickness, pad-tooth adaptation, and curing light penetration underneath the pad. The null hypothesis tested was: there is no difference between the three pad designs.

MATERIALS AND METHODS

Teeth

Extracted human maxillary and mandibular first and second premolars were either stored in a 10:1 water/bleach solution or a 0.5% Chloramine T solution. The buccal surfaces of the teeth were free of any caries, fractures, enamel defects, and restorations. Forty five teeth were selected and grouped by type: maxillary premolars, mandibular first premolars, and mandibular second premolars. The premolars of each type were then randomly distributed into one of the three bracket groups: New bracket, Foil mesh, and Milled mesh (Figure 1).

Brackets

Three brackets were used and details of each are provided in Table 1. The mean bracket pad surface area (mm^2) was calculated by measuring 10 bracket pads of each type (maxillary premolar, mandibular first premolar, and mandibular second premolar) with a digital caliper.

Shear bond strength test bonding procedure

To increase retention, two circumferential retention grooves were placed in the roots of the forty five premolars with a high speed handpiece and carbide bur, and the teeth were embedded in stone to the approximate level of the cemento-enamel junction or horizontally so that the lingual surfaces were embedded up to the central groove and the facial surfaces were left exposed. All brackets were cleaned with ethyl alcohol. The buccal tooth surfaces were cleaned with pumice slurry. The buccal enamel was etched with a 37% phosphoric acid etching gel for 30 seconds, thoroughly rinsed for 10 seconds and dried for 10 seconds with oil-free compressed air. A uniform coat of Transbond XT primer (3M Unitek, Monrovia, CA) was applied to each tooth and air thinned with oil-free compressed air. A small amount of Transbond XT adhesive (3M Unitek, Monrovia, CA) was applied to each bracket pad. A force of greater than 200 grams has been recommended for direct bracket bonding in a simulated clinical situation to achieve a thin resin composite layer and sufficient spreading of the adhesive paste (Muguruma et al, 2010). To achieve this, all of the brackets were placed in the middle of the buccal surface along the height of contour with a Richmond pressure gauge (ORMCO, Glendora, CA) using 227 grams of force for 10 seconds. Excess adhesive was carefully removed with a scaler prior to polymerization. Brackets were light-cured with an Ortholux LED curing unit (3M Unitek, Monrovia, CA) for 10 seconds directed to the Mesial edge and 10 seconds to the Distal edge using a positioning jig which oriented the light 45 degrees to the tooth surface. The irradiance of the light-curing unit was tested with a LED radiometer and recorded prior to each procedure (820-830 mW/cm^2). The bonded teeth were stored out of direct light in tap water for 4 days at room temperature.

Shear bond strength procedure

During testing, the teeth were oriented so that the buccal surfaces and brackets were parallel to the applied force. A metal jig with a universal joint was fit to the crosshead of a universal testing machine (Qtest, MTS Systems Corporation, Cary, North Carolina) and against the gingival wing of the brackets (Figure 2). An occlusal-gingival load was applied (at 1mm/min) to the brackets producing a shear force close to the bracket-tooth interface. Debonding forces (N) were recorded and converted to shear bond strength (MPa) by dividing by the appropriate bracket pad surface area.

Adhesive Residual Index

The debonded teeth and brackets were examined and fracture locations were analyzed at 10x magnification with a stereomicroscope using the adhesive remnant index (ARI) developed by Årtun and Berglund (1984):

ARI-0 = 0% adhesive on the tooth or 100% adhesive on the bracket

ARI-1 = under 50% of the adhesive remains on the tooth or over 50% adhesive remains on the bracket.

ARI-2 = over 50% of the adhesive remains on the tooth or under 50% adhesive remains on the bracket

ARI-3 = 100% of adhesive remains on the tooth or 0% of the adhesive remains on the bracket

Adhesive resin thickness, pad adaptation, and light penetration analysis bonding procedure

A single maxillary premolar was selected and attached to a centering device in a lathe (Figure 3a). Transbond XT adhesive (0.02g) was placed on 15 maxillary premolar brackets (5 NB, 5 MM, 5 FM), and the brackets were placed onto the non-etched buccal enamel surface with light pressure. An index of the bracket wings was placed at the end of the Richmond gauge to allow for a consistent and repeatable bracket engagement. With the use of the centering device, the tooth was moved horizontally into a Richmond gauge fixed into the chuck of the lathe (Figure 3b) until it registered 227g of force (Figure 3c). Excess adhesive was carefully removed with a scaler prior to polymerization. The adhesive was light-cured with an Ortholux LED curing unit in the same manner as for the bond strength specimens. The brackets were carefully debonded with an angulated bracket removing plier (Orthopli Company, Philadelphi, PA) to ensure complete removal of the bracket with adhesive attached, and these were embedded in a slow cure epoxy resin (Figure 4a) and allowed to set for 24 hours out of direct light. The samples were cut at the pad edge and center into approximately two 1mm thick cross-sections occlusal-gingivally (Figure 4b) on a diamond blade saw (Struers).

Resin composite thickness and pad adaptation

Four thickness measurements (occlusal, gingival, and the thickest and thinnest layer under the bracket) were made on the mesial and distal sides of the sections with a stereomicroscope at 175x magnification using the Dino-Capture software (AnMo Electronics Corporation, Taipei City, Taiwan) to the nearest 0.1 m (Figure 5 and 6). In order to remove any metal spurs that may have embedded into the resin during the sectioning procedure, the cross-sections were polished with 1200 grit SiC paper and 5 m alumina powder mixed with a diamond compound thinner lubricant prior to making the measurement of the thinnest layer under the bracket pad. The mean overall thickness was calculated by taking the sum of the eight occlusal and gingival measurements per bracket. Fifteen measurements (5 per group) were performed and duplicate measures were made by the same person to calculate the error of measurement.

Light penetration under the bracket

Transmission Fourier-transform infrared (FTIR) spectroscopy (Nicolet Continuum FTIR Microscope, Thermo Fischer Scientific Inc., Waltham, MA) was performed in Near-Infrared (IR) mode (4 cm^{-1}, 100 scans, 100x100 m aperture) through the cross sections 7 days after the bonding procedure. Spectra were recorded in 26 samples (8 NB, 8 FM, 10MM). A spectrum of the polymers were compared within the same sample at two different pad locations, the edge and the center, to compare the amount of conversion of the carbon double bonds (Figure 7) using the aliphatic C=C peak (6165 cm^{-1}) which correspond to the bonds between the carbon and the methacrylate groups in the methacrylate monomers (Figure 8). The area under the aromatic C...C ring peak (4625 cm^{-1}) from the Bis-GMA monomer provided an internal reference.

The Transbond XT adhesive was also tested by curing in thin films to determine the degree of cure when directly exposed to the curing light:

<u>Uncured Adhesive:</u> A film of uncured Transbond XT adhesive was placed between glass slides at three thicknesses (0.90mm, 1.2mm, 1.4mm) using spacers and spectra were recorded.

<u>Cured Adhesive:</u> The adhesive films between glass slides were cured with the Ortholux LED curing unit for 10 seconds and FTIR spectra were recorded. Then, the films were exposed to an additional 10

seconds of light curing and spectra re-recorded, and then again after aging dry and in the dark for one week.

The degree of conversion (DC%) was calculated at all three time points for the thin film samples using the following formula:

$$DC = \frac{[(\text{Area of C=C/Area of AR})_{uncured} - (\text{Area of C=C/Area of AR})_{cured}]}{(\text{Area of C=C/Area of AR})_{uncured}}$$

A one-way analysis of variance (ANOVA) was used to compare the shear bond strength between the three groups. A chi-squared test was used to compare the ARI scores between the groups. A one-way ANOVA/Tukey's post-hoc comparison test was also performed to determine whether significant differences exist in the overall adhesive thickness at the occlusal and gingival edge of the pad and the thickest and thinnest adhesive layers underneath the pad between the three groups. A one-way ANOVA and t-test were also performed to determine if there were significant differences in the adhesive thickness along the occlusal and gingival pad edges in both the occlusal-gingival and mesial-distal directions within each group. Measurement error (0.01 mm) of adhesive thickness was estimated using Dahlberg's Formula on 15 repeated measurements. Paired t-tests were used to determine if a significant difference existed between the cure of the adhesive at the edge and center of the pad within each group. All statistical analyses were performed at a 0.05 level of significance.

RESULTS

Shear bond strength (SBS)

The foil mesh pad had the highest mean SBS (14.74 ± 4.24 MPa), followed closely by the milled mesh pad (14.43 ± 3.58 MPa), and the new bracket pad had the lowest mean SBS (12.22 ± 2.97 MPa), but the differences were not significant (p=0.129; Figure 9). A power analysis indicated that a sample size of 60 per group would be required to show that a difference of 2MPa is significant at 80% power.

ARI scores were the same in all three groups (x^2=0.600, p=0.741), with failure predominantly at the enamel-adhesive interface (ARI-1); 73% for the NB group, 67% for FM group, and 60% for the MM group (Table 2). None of the samples showed complete enamel bond failure (ARI-0) or complete bracket bond failure (ARI-3).

Resin composite thickness and pad adaption

The mean overall adhesive thickness along the occlusal and gingival edges of the FM, 0.09mm, was significantly less than the NB and MM groups, 0.14mm and 0.17mm, respectively (Table 3). The thickness of adhesive resin underneath the bracket was also significantly different between the groups, p<.001 (Table 3). The NB had a significantly thicker adhesive layer extending into the retentive feature, 0.43mm, compared to the FM, 0.27mm, and the MM, 0.20mm. Furthermore, the NB and MM groups had significantly thinner layers of adhesive at the pad's most proximal position to the tooth surface, 0.01mm and 0.02, respectively, compared to the FM group, 0.07mm. The pad was in direct contact with the tooth in 13/20 NB and 10/20 MM of the cross-sections, while none of the FM pads were touching the tooth.

The FM and MM showed a significant difference in the occlusal-gingival adaptation with a thicker layer at the occlusal pad edge than at the gingival (0.12 mm vs. 0.06 mm and 0.20 mm vs. 0.14

vmm, respectively). The NB did not show a significant difference, p=0.08. There was no significant difference in the mesial-distal pad adaptation within the groups (Figure 10).

Light penetration under the bracket pad

The mean degree of cure (DC) of the adhesive at the edge and center of the three brackets ranged from 93.7 to 96.0% (Figure 11). For the bracket-adhesive cross-sections, the carbon double bond peak (C=C) area at the edge of the bracket versus at the center was statistically different in the foil mesh and milled mesh bracket pad designs (p=0.012 and p=0.016, respectively; Table 4). The difference in the degree of cure between the center and edge was about 2% in both groups. The new bracket pad did not show a significant difference (p=0.856). DC of the Transbond XT baseline cured in a thin film was 46% after 10 seconds of cure, 50% after 20 seconds of cure, and 61% one week later (Figure 12).

DISCUSSION

All three bracket pads demonstrated clinically adequate bond strength, with means being well above the 6-8 MPa recommended by Reynolds et al (1975). The SBS reported were also within the lower range of what is required of a bracket to withstand maximum biting forces (13-26 MPa; Fields et al, 1986).

The mean SBS reported in the present study for the FM and Transbond XT (14.74 $\pm$ 4.24 MPa) is similar to what has been reported by the manufacturer (15 $\pm$ 5 MPa). It is difficult to make direct comparisons to previous studies due to the difference in bonding methods and materials, but the results appeared to be in the range (5.2$\pm$3.9 to 17.2$\pm$3.2 MPa) of what has been reported in the past for brackets bonded with Transbond XT, (Reimann et al, 2012; Iijima et al, 2007; Bishara, 1999; Bishara, 2004).

The ARI provides information on the weakest part of the bonding system. If the tooth is prepared properly, in the absence of oral contamination, the failure site of metal brackets has been identified in many studies as the bracket-adhesive interface (Reynolds and von Fraunhofer, 1976; Faust et al 1978, Dickinson and Power, 1980; Regan and van Noort, 1989; Jost-Brinkmann et al, 1992; Bishara et al, 1999, Arici et al, 2005, Algera et al, 2011). In contrast, a majority of ARI-1 scores were reported in the present study, indicating the weaker bond to be at the enamel-adhesive interface for all groups. There was a trend for adhesive failure at the cement-bracket interface along the pad edge nearest to the applied force. This initial failure location has been reported for Transbond XT adhesive when subjected to a shear bond strength test (Algera et al, 2010). It also has been shown that the fracture pattern of Transbond XT ultimately ends as an enamel-adhesive interface at the far end of the bonding surface (Algera et al, 2010). In contrast, the majority of the specimens in this study showed a transition to an enamel-adhesive failure much closer to the applied force, resulting in more ARI-1 scores. This suggests that the loading scheme in the present study, where the force was not directly applied to the bracket base, may have produced a slight moment rather than a pure shear force. The explanation for the early transition into an enamel-adhesive failure in the current study is unclear, but appeared to be consistent between the groups.

The variability of the appearance of the NB pad design in each cross-section made it difficult to analyze and compare the adhesive thickness under the pad (Figure 5). Therefore, the thickest and thinnest layers of adhesive between the tooth and the pad surface in each cross-section were compared. It has been reported that a light-cured resin achieved maximum bond strength at 0.2 mm and was considerably weaker at 0 mm (Jost-brinkmann et al, 1982; Arici et al, 2005). It has also been reported that shear bond strength decreased with increased adhesive thicknesses of 0.5 mm (Arici et al, 2005) and 0.75 mm (Schecter et al, 1980). The mean overall thickness along the pad edges were within an acceptable range (0.09 mm to 0.17mm) for a light-cured adhesive in all three groups in this study. Though the thickness of the adhesive layer beneath the pads of the NB (0.43 mm and 0.01 mm) and MM (0.02 mm) were in the range of what had been reported as producing weaker bonds, they did not appear to affect the mean overall bond strength.

The average bracket pad dimensions of the NB was the largest (12.47 mm^2), followed by the MM (11.54 mm^2), and then the FM (10.74 mm^2). When considering the force (N) required to shear the brackets, the MM presented with the highest force required to debond (170 N), followed by the FM (158 N), and then the NB (152 N). The larger surface area of the bracket pad may increase the overall force required to debond, but the increased size results in a reduction in the bracket-tooth adaptability (Cozza et al, 2006). This may explain the significantly greater overall mean thickness of resin along the edges, as well as a direct metal to tooth contact in more than half of the cross-sections in the larger MM and NB designs. In addition to a reduction in bracket-tooth adaptability, larger designs tend to be less esthetic and also allow for more surface area that can act as a site for plaque retention.

The thickness of the cross-section samples used to measure the degree of conversion (DC) varied considerably between 0.783 to 1.113 mm. To ensure that the FTIR spectra were not influenced by the thickness of the adhesive sample, spectra of uncured adhesive in a thin film were recorded at different thicknesses. The uncured carbon double bond (C=C) to aromatic ring (AR) ratio (C=C:AR) was similar for all three thicknesses, at approximately 1:1, suggesting that thickness did not affect the spectra for the peaks of interest and that the areas under the C=C peak could be compared directly between specimens. In addition, the thin films were cured and immediately tested at 10 seconds of cure, at an additional 10 seconds of cure (20 seconds total), and one week later, to use as a baseline comparison and to assess the DC of the adhesive when directly exposed to the curing light. The Transbond XT DC calculated for the thin films (Figure 12) was similar to what has been reported in previous studies (Eliades et al, 2000; Cerveira et al, 2010; Shinya et al, 2009).

In order to accurately calculate the DC in the samples, an uncured bracket/adhesive cross-section is necessary to obtain an uncured C=C:AR ratio. Unfortunately, the process of embedding the specimen in epoxy resin and the sectioning procedure made it impossible to obtain an uncured sample in the same condition as the rest of the specimens. Therefore, the ratio calculated from the spectra of the uncured adhesive films (1:1) was used to calculate the DC in the samples (Figure 11). The DCs ranged from 93.7% to 96.0%, which was unusual and unlikely for a dimethacrylate resin, especially in light of the cure of the thin films (61%). In contrast, a lower DC has been reported for a light-cured orthodontic adhesive cured under a bracket (32.4%) compared to a film of adhesive cured on a glass slide (54.7%) (Shinya et al, 2009).

The significant differences reported for the adhesive cured in a thin film and those from the cross-section samples may be due to an unmatched C=C:AR ratio between the baseline material cured in a thin film and the sample cross-sections (1:2.5 vs. 1:18). A trend for significantly decreased absorbance of the C=C molecules and increased absorbance of the AR appeared within the cross-section samples compared to the cured baseline material. A reduced signal could skew the absolute absorbance values at different wavelengths. The proximity of the metal and/or epoxy embedding resin to the adhesive resin may also have reduced the signal strength. In addition, when viewing the composite under the FTIR microscope, the filler particles were more apparent in the retentive features (i.e. within the grooves) than at the edge of the bracket (Figure 7). It is hypothesized that the adhesive may undergo a "sieving action" when placed under pressure during bracket placement, pushing the monomer outward and leaving most of the filler particles within the retentive features. A higher amount of filler particles under the bracket may have also reduced the signal through the paste.

Regardless of the unusually high DCs recorded in the adhesive under the bracket, the difference in C=C conversion at the edge and center of the pad was of primary interest. Therefore, the area under the C=C peaks for the spectra recorded from within the grooves and at the edge of the bracket were directly compared for each specimen, and the differences suggest that the design may influence the light penetration beneath the bracket pad.

The FM bracket has the smallest surface area. Therefore, one would expect it to have the best light penetration. To the contrary, the FM pad showed a higher cure at the edge than in the center (Figure 11). It is possible that the undercuts present in the foil mesh made it more difficult for light penetration and/or that the mesh acts as a wall around the bracket pad, thus blocking the light. The MM design showed significantly more conversion of C=C at the center compared to the edge and the NB showed no difference between the two locations. In contrast to the FM, the MM and NB have features that may channel the light from the edge to the center thus enhancing the light penetration (Figure 1). In any case, the degree of cure was sufficient enough under all conditions to produce adequate bond strengths, suggesting that ample light energy was transported beneath all of the bracket designs.

CONCLUSION

Bracket pad design significantly influenced the thickness of adhesive resin, pad adaptation, and light penetration. However, although significant differences were observed, they did not significantly affect the bracket pad's overall bond strength or location of bond failure. Light penetration under the bracket pad was sufficient in all three designs. The new bracket pad performed similarly to the other two widely used designs, but no distinct advantages were evident.

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FIGURE LEGENDS

Figure 1. Bracket pads a) New Bracket b) Foil Mesh c) Milled Mesh

Figure 2. Shear Bond Strength Test Metal Jig

Figure 3. Centering device. Richmond Gauge with bracket wing index.

Figure 4. a) Bracket embedded in epoxy b) Example of bracket/composite sample cross-sections

Figure 5. Occluso-gingival cross-sections x84 magnification; Representations of the Distal (AD), Center-Distal (AM), Center-Mesial (BD), and Mesial (BM)aspects of the bracket pad

Figure 6: Example of thickness measurements x175 magnification a) New Bracket b) Foil Mesh c) Milled Mesh

Figure 7. FTIR Near-IR transmission locations, 100x100 μm aperature a) Edge b) Center

Figure 8. FTIR Spectra a) Full spectra with arrows indicating the C=C and AR peaks b) C=C peak at 6165 cm^{-1} wavenumbers c) AR peak at 4625 cm^{-1} wavenumbers

Figure 9. Shear bond strengths of each group

Figure 10. Adhesive layer thickness within each group

Figure 11. Mean degree of cure of the Bracket/Adhesive cross-section samples

Figure 12. Mean degree of cure of the Transbond XT baseline films

Figure 1.

a) b) c)

Figure 2.

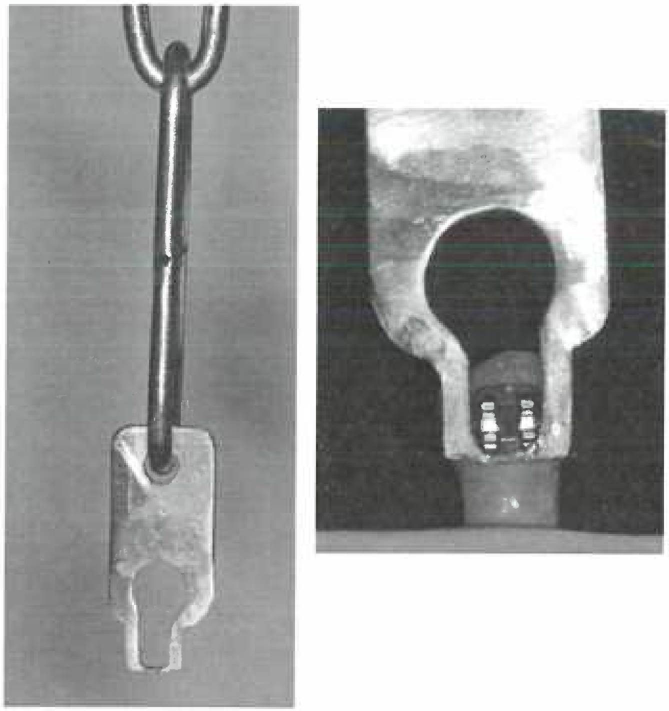


Figure 3.

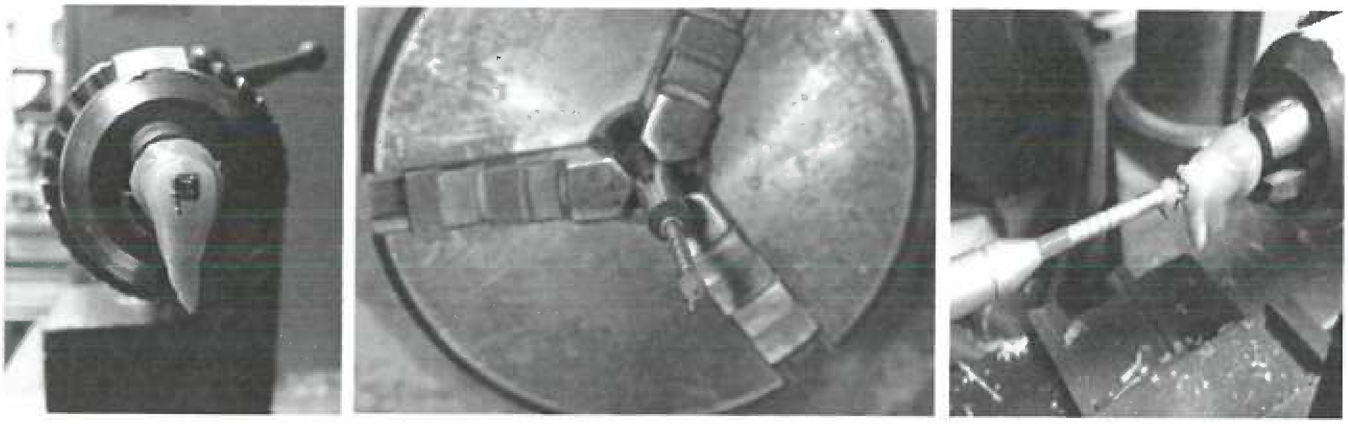
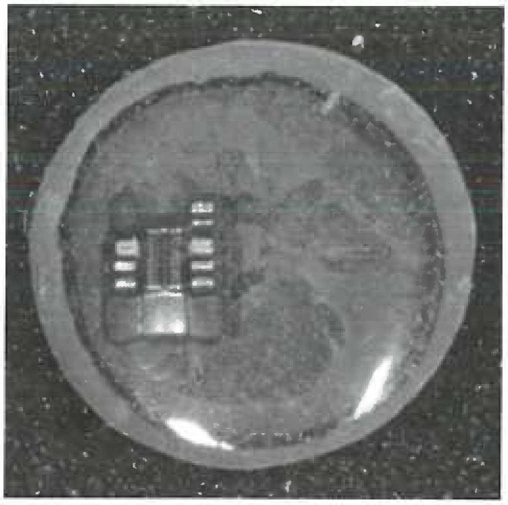


Figure 4.

a)



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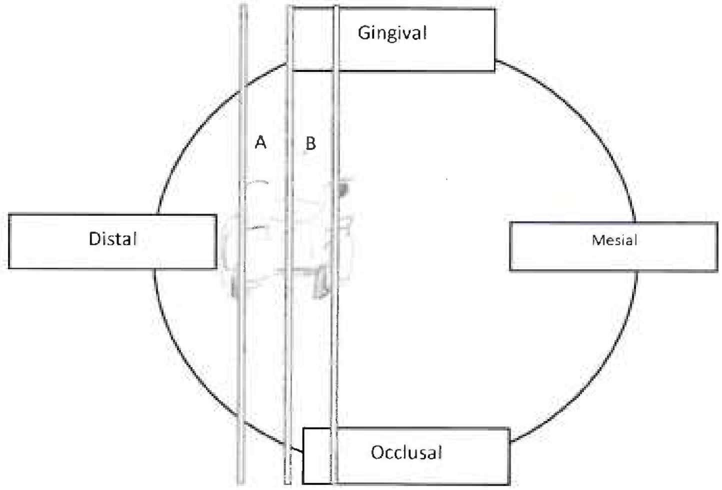

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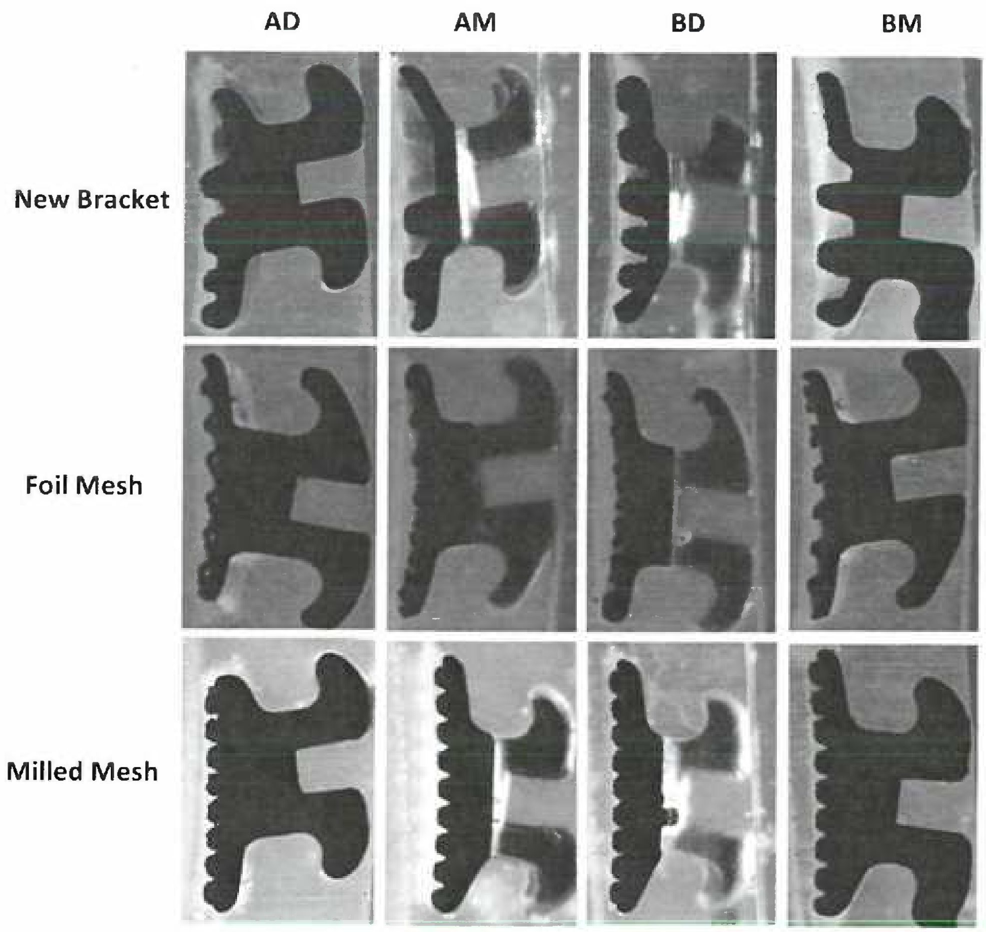


Figure 6.

a) b) c)

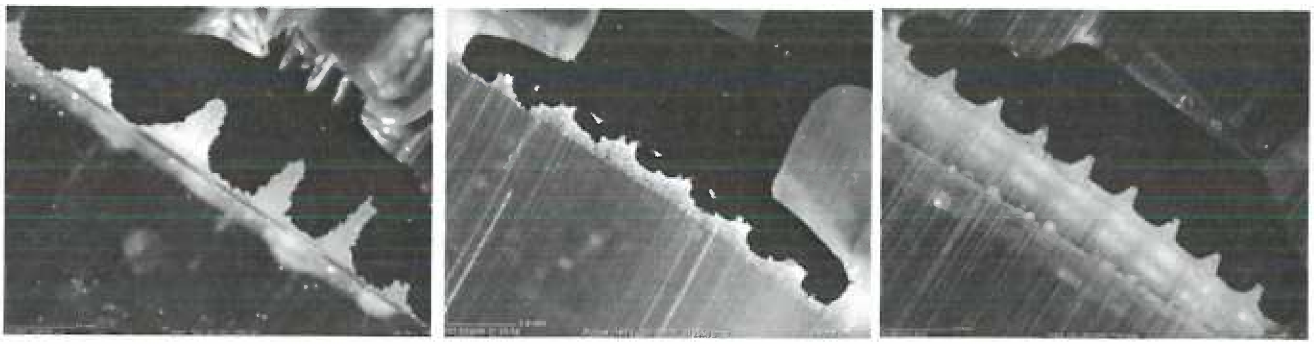


Figure 7.

a) b)

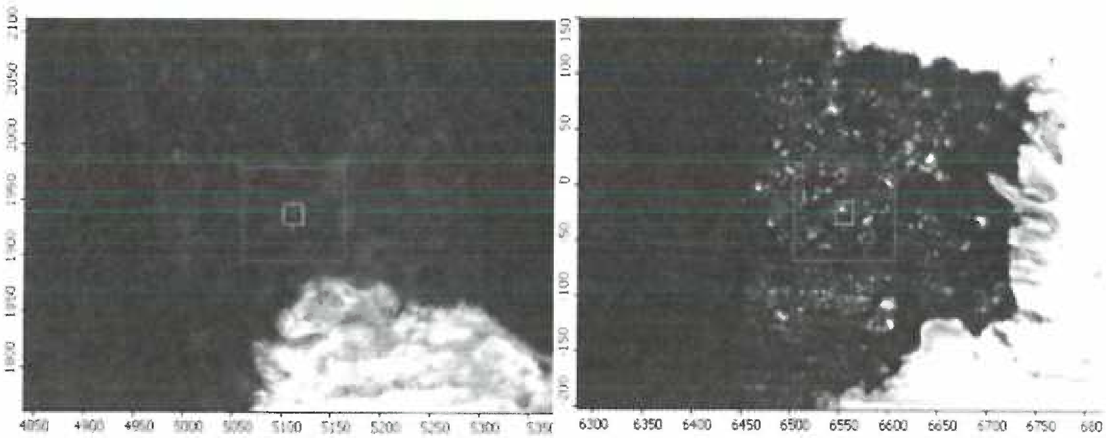
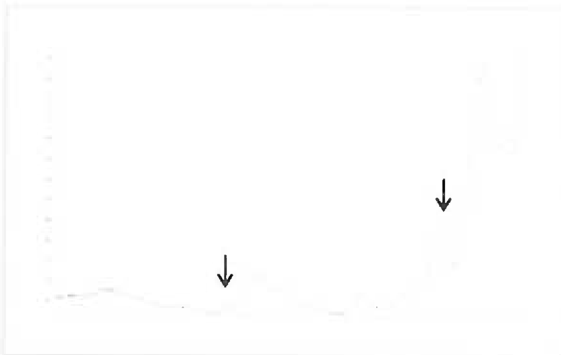
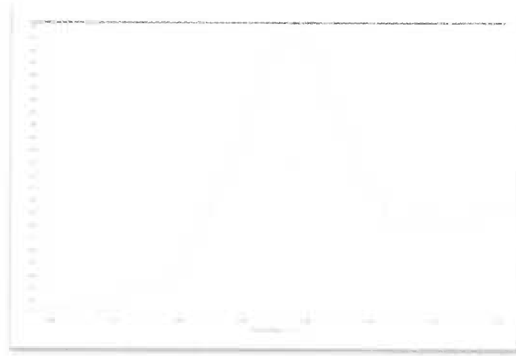


Figure 8.

a)

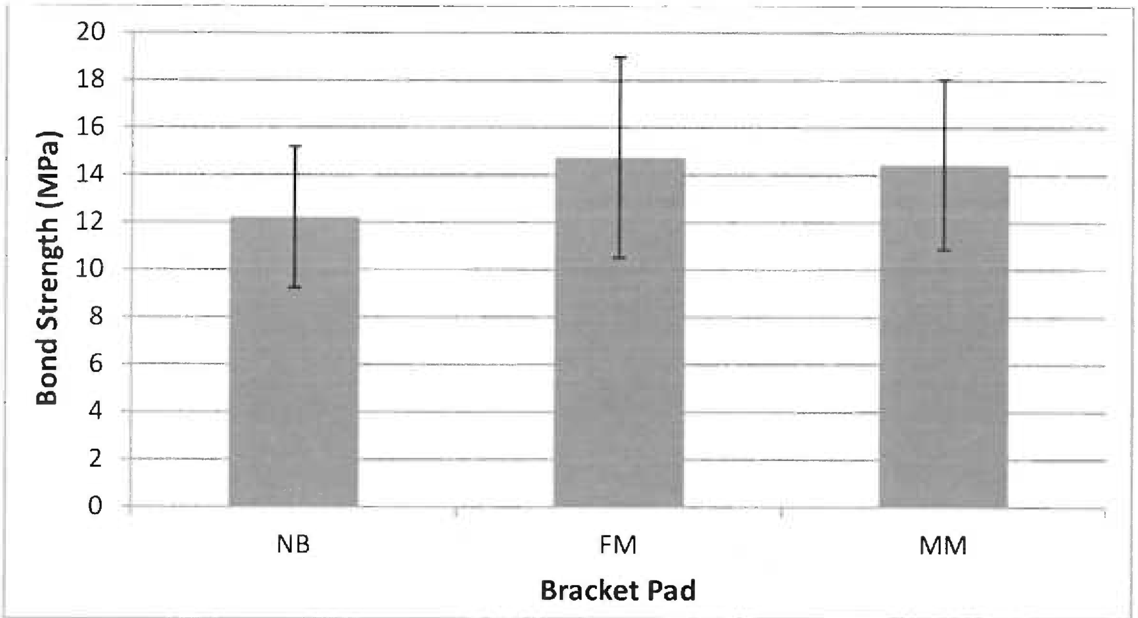


b)



c)

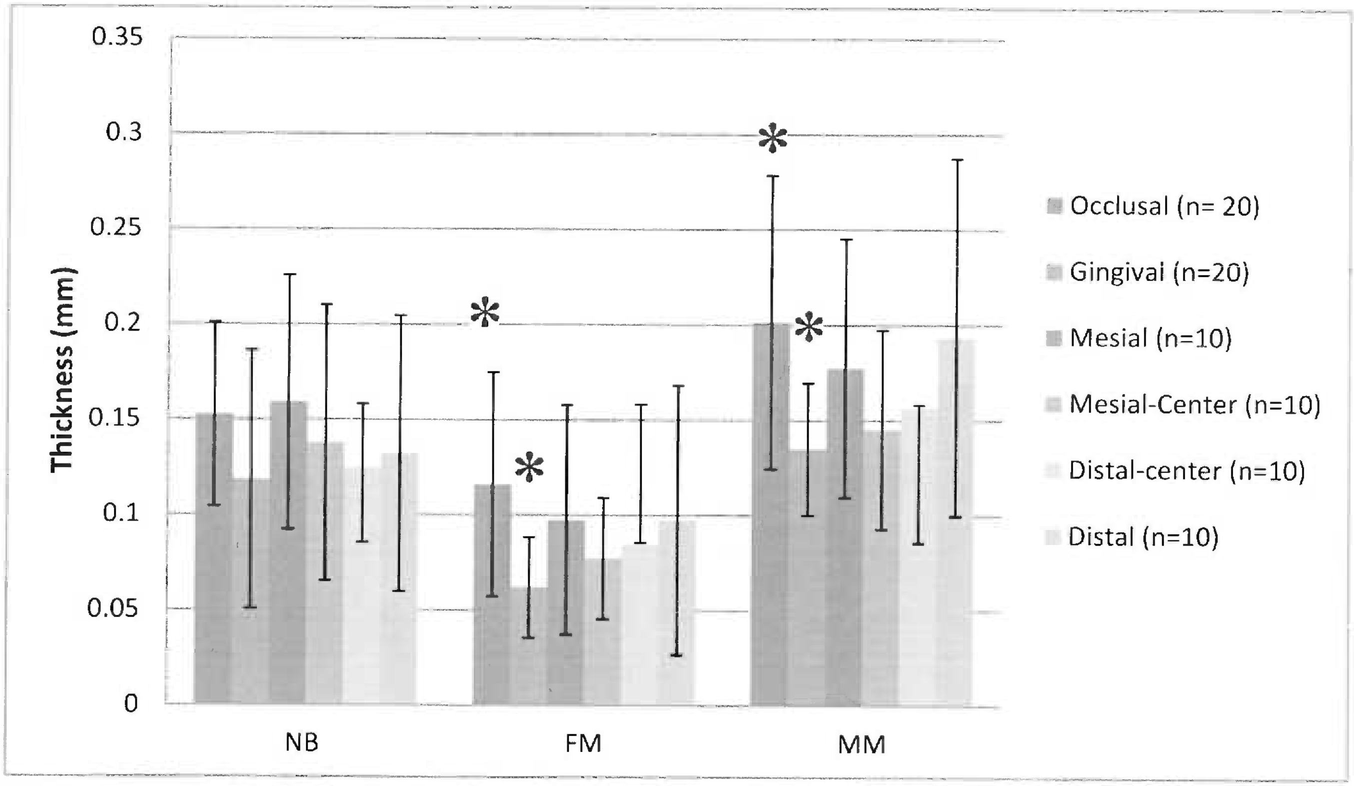
Figure 9.



NB, new bracket pad; FM, foil mesh pad; MM milled mesh pad; n=15; error bars, standard deviation

ANOVA: Groups were not statistically significant, p=0.129

Figure 10.

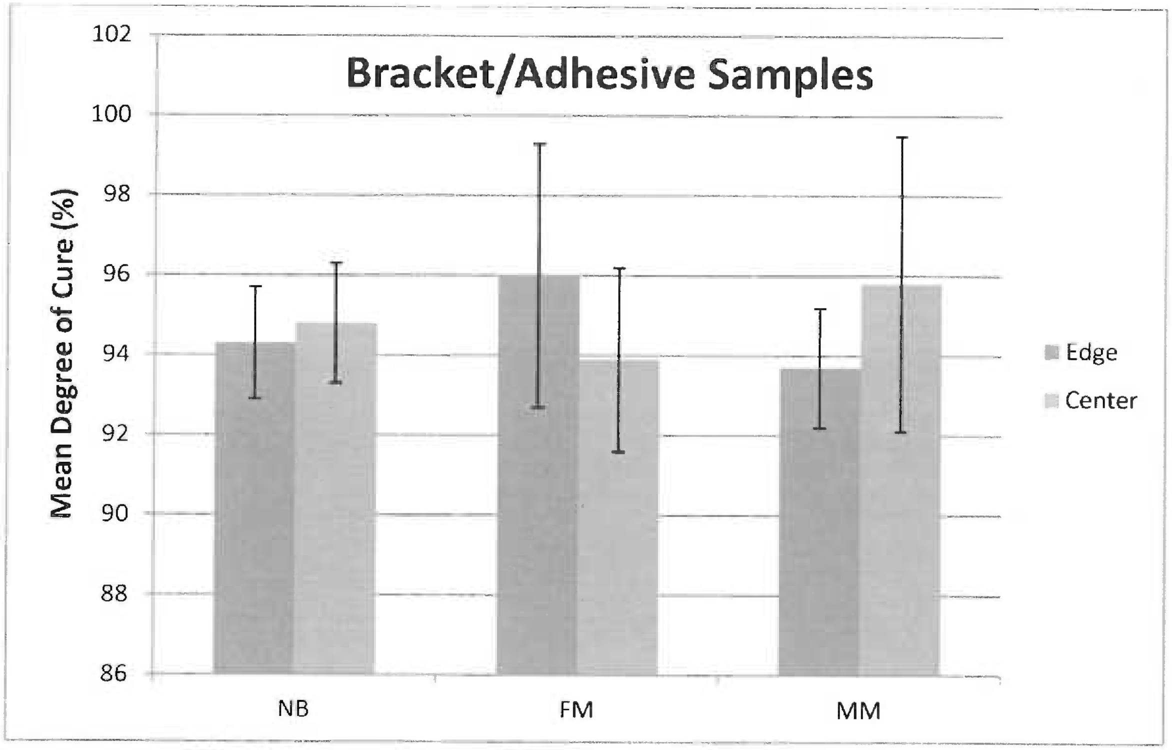


* Indicates significant difference within group

ANOVA: Mesial vs. Mesial-Center vs. Distal-Center vs. Distal; T-test: Occlusal vs. Gingival. Groups that are significantly different from one another, $p<0.01$ level of significance

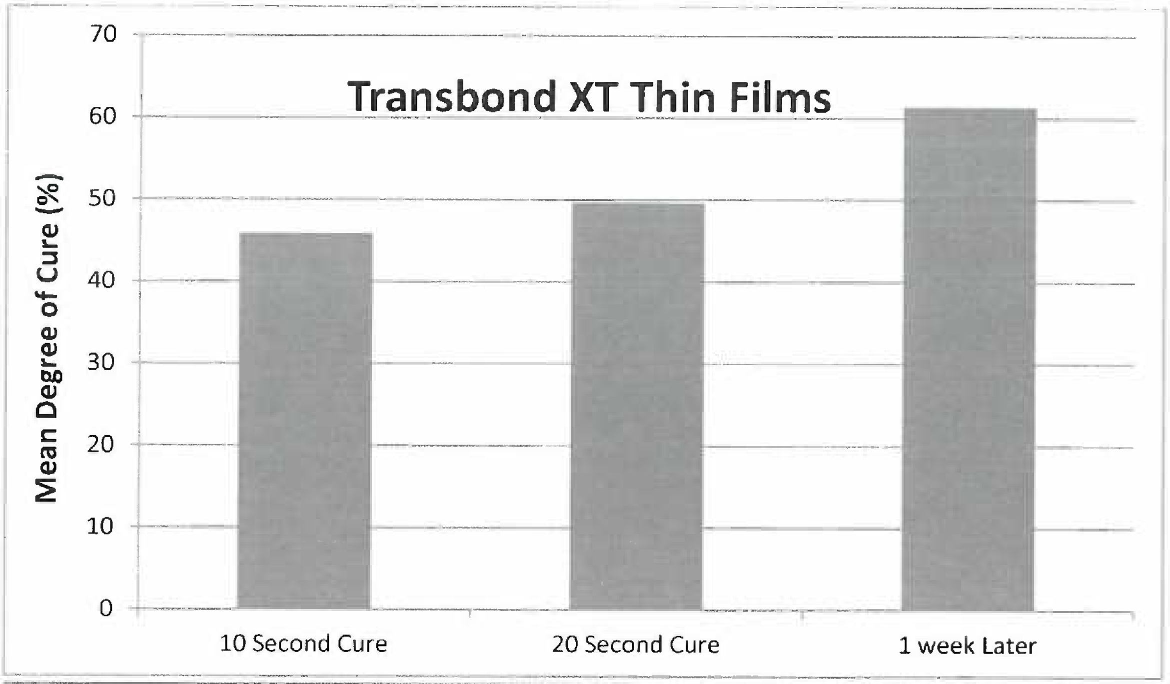
Error bars, standard deviation; n, sample size

Figure 11.



NB, new bracket pad; FM, Foil mesh pad; MM, milled mesh pad; error bars, standard deviation

Figure 12.



Transbond XT Cured in a thin Film at 0.9 mm, 1.2 mm, 1.4 mm thicknesses

Degree of cure calculated by taking the C=C/AR ratio of uncured-cured/uncured

Spectra taken on same specimen immediately after 10 second cure, immediately after an additional 10 second cure (20 seconds total), and one week later

Table 1. Bracket Description

	Manufacturer	Fabrication Method	Surface Area	Pad Design	Surface Treatment
New Bracket (NB)	Ortho Classic Corporation McMinville, OR	Metal Injection Molding (MIM)	U4/5 $12.30mm^2$ L4 $12.41mm^2$ L5 $12.71mm^2$	Novel	Micro-etched
Victory Series Low Profile Bracket (FM)	3M Unitek Monrovia, CA	Milled	U4/5 $10.73mm^2$ L4 $10.72mm^2$ L5 $10.78mm^2$	Brazed 80-gauge Foil Mesh	Micro-etched
Biomim Bracket (MM)	Ortho Classic Corporation McMinnville, OR	Metal Injection Molding (MIM)	U4/5 $12.07mm^2$ L4 $11.22mm^2$ L5 $11.33mm^2$	Pad-Lok 100 Foil Mesh Equivalent	Micro-etched

Table 2. ARI[a] Scores and Percentages

Value	Criterion	Interpretation	NB	FM	MM
ARI 0	0% of the adhesive left on tooth	Complete failure at adhesive-enamel interface	0	0	0
ARI 1	<50% of the adhesive left on tooth	Primary failure at adhesive-enamel interface	11/15 (73.3%)	10/15 (66.7%)	9/15 (60%)
ARI 2	>50% of adhesive left on tooth	Primary failure at adhesive-bracket interface	4/15 (26.7%)	5/15 (33.3%)	6/15 (40%)
ARI 3	100% of adhesive on tooth	Complete failure at adhesive-bracket interface	0	0	0

[a] Adhesive Remnant Index

Chi-squared Test: Groups were not statistically significant, x^2=0.600 p=0.741

Table 3. Mean Overall Adhesive Thickness at the Edge and Thickest and Thinnest Measurements Under the Bracket Pad Between Groups

Group	Mean Overall thickness (mm)	Thickest (mm)	Thinnest (mm)
NB	0.14 (0.01) [a]	0.43 (0.07) [a]	0.01 (0.03) [a]
FM	0.09 (0.01) [b]	0.27 (0.02) [b]	0.07 (0.13) [b]
MM	0.17 (0.03) [a]	0.20 (0.08) [c]	0.02 (0.03) [a]

Mean overall thickness for the pad along the occlusal and gingival edges (n=5), Mean thickness and thinnest layer underneath the bracket pad (n=20)

Groups with different lettering are significantly different from one another

ANOVA/Tukey's Post Hoc: Mean overall thickness: FM vs. NB P=.006 level of significance, FM vs. MM P<.001 level of significance, Thinnest and thickest: P<0.001 level of significance

Table 4. FTIR readings at the edge vs. center of the pad within each group

Group	n	Mean Difference in C=C Peak Area Edge – Center (SD)	P-value
NB	8	0.0043 (0.0654)	0.856
FM	8	-0.0628 (0.0532)	**0.012**
MM	10	0.06974 (0.0750)	**0.016**

NB, new bracket pad; FM, foil mesh pad; MM milled mesh pad; n, sample size; C=C, Area under double carbon bond peak; AR, Area under the aromatic ring peak, SD, standard deviation

Paired T-test: Edge vs. Center C=C with different letters were significantly different at P=.05 level of significance

C=C peak was measured at approximately 6165 cm^{-1} wavenumbers, AR peak was measured at approximately 4625 cm^{-1}

LITERATURE REVIEW

SPECIFIC AIMS

Bond failure of orthodontic brackets can be a nuisance to both patients and orthodontists. An increase in bond failures can result in compromised treatment efficiency due to an increase in the number of appointments, increase in appointment time, and/or a relapse in tooth movement. Bond failure has been a problem complicating treatment and progress since the introduction of bonding materials to orthodontics more than 40 years ago. Various bonding methods and protocols have been developed to minimize bond failures, yet clinicians and researchers still find a significant rate of failures during treatment.

Bond survival has been reported to vary significantly between tooth types, with more failures reported in the buccal segment than the labial segment (Newman, 1978; Lovius et al 1987; Linkletter and Gordon, 2003; Millet et al, 1998; Berwani et al, 2008). In vivo bond failure rates have been reported widely in the orthodontic literature, ranging from 5 percent for upper incisors to 11 percent for premolars (Millet et al, 1998). A wide range of bracket failure rates and times have been reported in the literature. When bonded with a light-cured adhesive resin, failure rates have been reported to be as high as 23% (Lovius et al, 1987) and as low as 6% (Millet et al, 1998). Likewise, the mean time between bonding and failure has been shown to be as low as 245 days (Bherwani et al, 2008) and as high as 442 days (Millet et al, 1998).

During active orthodontic treatment, the bond strength between the bracket and tooth surface must not only be strong enough to allow for the delivery of orthodontic forces, but must also be sufficiently resilient to withstand masticatory loads. During treatment, it is the occlusal forces that will likely cause unwanted bonding failures when standard bonding techniques have been implemented. Occlusal loading occurs directly by tooth or food bolus contact with the bracket or archwire. It has been reported that bond strength of 6-8 MegaPascals is clinically sufficient for orthodontic treatment (Reynolds, 1975). It has been shown that the point of vulnerability in adhesive bonds is at the transition between the bracket and adhesive and this area has been shown to be the most frequent area of fracture in shear bond strength tests (Reynolds and von Fraunhofer, 1976; Faust et al 1978, Dickinson and Power, 1980; Regan and van Noort, 1989; Jost-Brinkmann et al, 1992; Eberhard et al, 1994; Bishara et al, 1999, Arici et al, 2005). The shear bond strength of the composite material can be affected by several factors; the bonding and/or light curing technique, the type and/or thickness of adhesive, the oral environment, and the bracket base design, surface area, and surface treatment.

Orthodontic manufacturers are continually developing new materials or designs to aid in the retention of orthodontic appliances and it is well documented that the surface pattern geometry of the bracket pad has a significant effect on the bond strength to enamel (Sharma-Sayal et al, 2003; Wang et al, 2004). Bracket pad retention can be either mechanical or chemical. Mechanical undercuts can be provided by fine mesh that is brazed to the bracket pad or undercuts that are incorporated into the bracket pad design through casting, milling, or metal injection molding (MIM). The undercuts in the bracket base allows for the orthodontic adhesive to extend into it prior to polymerization, thus interlocking the adhesive to the bracket pad. Conventional resin relies on this mechanical interlock for the attachment of a metal bracket to an adhesive resin (Ireland and Sherriff, 1994). This mechanical interlock has been shown to be compromised by pad designs that show an increased incidence of adhesive voids, incomplete adhesive polymerization, and/or those designs that incorporate stress concentrations and uneven stress distribution within the adhesive layer. Some brackets are additionally sandblasted, chemically-etched, or sintered with porous metal powder to enhance the retention of a certain pad design.

Ortho Classic has developed a new bracket pad design in hopes of decreasing bracket bond failures. They believe that their design will allow for an even layer of bonding material, a decrease incidence of voids within the adhesive layer, a reduction in stress concentrations, and an even dispersion of forces, thus leading to increased mechanical retention. The purpose of this research project is to compare the shear bond strength of a new integral MIM'd bracket pad design to a conventional 80-gauge woven mesh pad (MBT Victory, 3M Unitek) and integral MIM'd 100-gauge mesh pad (Pad-Lok, Ortho Classic). In addition, an evaluation of adhesive thickness, uniformity, and cure will be performed. If a bracket pad design can significantly affect the shear bond strength of a specific bonding material, bracket design may influence a clinician's decision when choosing which bracket system to use on their patients. Likewise, the new design may aid researchers and product development teams to implement similar designs and/or to continue to develop more retentive bracket designs in the future.

Specific Aims of the study are:

1. To determine the shear bond strength of three different bracket pad designs. Null hypothesis states that there will be no difference in the shear bond strength between the groups.
2. To evaluate the adhesive remnant index (ARI) to determine the point of vulnerability in the adhesive bonds associated with the various bracket base designs. Null hypothesis states that there will be no differences in the adhesive remnant indices between the groups.
3. To evaluate the uniformity of the adhesive resin layer within the three bracket pad designs. More specifically, an evaluation of the resin thickness within individual bracket-resin composite cross-sections. Null hypothesis states there will be no difference between the adhesive resin layer uniformity between the groups.
4. To compare the polymer spectra, more specifically the double carbon bond peak/area, at the edge of the bracket versus at the center of the bracket for each bracket pad design. Null

hypothesis states that there will be no difference in double carbon bond spectra at the edge and center for each group.

ORTHODONTIC APPLIANCES

History

The history of orthodontics has been well documented by Norman Wahl (2005) and Robert P. Kusy (2002). Both authors report that orthodontics may date as far back as 400 B.C. and through their historical perspective it is clear that orthodontic appliances have evolved dramatically over the years.

Early orthodontic appliances have been shown to exist as far back as ancient Egyptians with archeologists' discoveries of mummies with crude metal bands wrapped around individual teeth. It is believed that they used catgut, a primitive attempt at orthodontic wire, to close dental spaces. In the 18th century, the French were leading contributors in the field of orthodontics. This was due in large part to a French dentist, Pierre Fauchard. Fauchard (1723) used a device known as the "Bandeau", a horseshoe-shaped piece of precious metal that helped to expand the dental arch. It has been documented that he corrected teeth with the use of silk thread and finger pressure. He also detailed the use of ligature wires and gold/silver mechanical devices. Around 1815, Christopher-Francois Delabarre introduced the wire crib, which marked the birth of contemporary orthodontics. He used the principle of the lever and screw in which he separated crowded teeth by means of swelling threads or wooden wedges. After Delbarre, several others followed. However, it wasn't until the mid-1800s, that Orthodontics as a science came into its own and the term "orthodontia" was coined by Joachim Lafoulon in 1841. Orthodontics in the late 1800s continued to develop through the works and writings of Norman W. Kingsley and J.N. Farrar who became known as the "Fathers of Orthodontics".

In the 1900s, Edward Angle became known as the "Modern Father of Orthodontics". Fauchard's "Bandeau" became the basis of Angle's E-arch that was developed in 1900. The E-arch consisted of bands on the first molars with wire ligatures tied to a heavy labial or lingual archwire that expanded ("E") the arch. However, the E-arch only tipped teeth, so in 1910 Angle developed the pin and tube appliance in order to bodily move them. The bands included a vertical tube attachment which connected to an archwire that consisted of multiple soldered pins. In order to move teeth, the pins were repositioned or re-soldered at subsequent appointments. The archwire was bent into the malocclusion and slowly "ironed-out", thereby slowly straightening the teeth. The pin-and-tube appliance was technique sensitive, difficult, time consuming, and only controlled the teeth in two planes of space. In addition, the pin-and-tube appliances use of a round archwire made controlling the torque of the teeth impossible. In 1916, Angle modified the pin-and-tube into an appliance with machined brackets that could closely fit a rectangular arch, known as the ribbon arch). The ribbon arch bracket was the first bracket developed and the ribbon arch of .022x.036 inch gold was held firmly with pins. Like the pin and tube, the ribbon arch had its shortcomings. There was still the need to "iron out" the arch wire and it was difficult to insert the ribbon arch between the horizontal molar tubes and the vertical bracket slots. To overcome some of these draw backs, Angle repositioned the bracket from vertical to horizontal in 1925 and inserted his rectangular wire on its edge into a rectangular slot. This became known as the edgewise appliance. The rectangular archwire was held into a .022x.028 inch slot with steel ligatures rather than being held and locked in with pins. The edgewise appliance was the first bracket capable of moving the teeth in all three planes of space simultaneously. Like in the past, the wire was adapted to the malocclusion and "ironed out". In the first half of the 19th century, the twin wire by Johnson, the Begg bracket, and the universal bracket by Atkinson were developed. Later, in attempts to achieve rotational control, Swain attached two brackets to a single base and called it the twin or "Siamese" bracket and Lewis soldered wings to the single bracket.

Several efforts were made in the early 20th century to build torque, tip, and angulation into the bracket. Larry Andrews took this pre-adjusted appliance idea to the next level by designing an appliance for each tooth which he called the straight wire appliance. Andrews' brackets controlled the position of the teeth based on his 6 keys to normal occlusion and it became the first appliance to combine torque, angulation, in-out, and offset. The straight wire appliance is the most commonly used today and there are several companies manufacturing different variations of the appliance. The focus on bracket development now involves bracket slot consistency and new materials and designs to decrease friction that will improve the precision and efficiency of tooth movement, as well as, bracket pad design to increase retention. Different bracket fabrication techniques are in place to aid in consistency; these include metal injection molding and precision-milling.

Bracket Materials

Three materials have been used to fabricate brackets: metal, polycarbonate, and ceramic. Metal brackets are the most widely manufactured and are made of stainless steel. Its benefits include lower cost, corrosion resistance, and strength. A major drawback of metal is that they are esthetically displeasing. Ceramic and plastic brackets are limited in strength, but offer the patient a more esthetic option. Plastic brackets were the first esthetic option to be introduced, but had limited success due to its water absorption and plastic deformation under load, therefore making them more susceptible to staining, wear, fractures, and distortions. The strength of ceramic made the material a better esthetic option. However, ceramic still remains inferior in strength to metal. Some major drawbacks of ceramic brackets are that they tend to be bulky, are brittle, and are subject to fracture, all of which makes it difficult for the orthodontist to use clinically.

Bracket retention

Mechanical retention is incorporated into the metal bracket pad design with the use of undercuts, grooves, and patterns and/or surface treatments such as sandblasting, chemically-etching, or sintering with porous metal. Ceramic brackets on the other hand can gain retention through both mechanical and/or chemical mechanisms. A chemical bond is achieved by creating an intermediate layer of glass on the bracket pad with the use of a silane coupler. This produces a chemical bond between the bracket and the resin composite adhesive.

Bracket pad designs

Resin composites do not bond to stainless steel, therefore one of the most important factors in retention of a metal orthodontic bracket is the type of bracket pad. Mechanical undercuts in the bracket base allows for the orthodontic adhesive to extend into it prior to polymerization, thus interlocking the adhesive to the bracket pad. Brackets can be classified into two groups: Soldered bases and Integral bases. Soldered bases include metal bases that are soldered to the bracket bodies. The bases can be perforated, made from mesh foils, or photoetched. Integral bases are those brackets and pads that are one inform piece. Integral bases are fabricated by casting, machine milling, or through metal injection molding techniques. The integral bases can be retention groove bases, mesh equivalent bases, waffle bases, etc. Some integral bases do not contain a retentive feature on the surface, but are flat and a retentive feature like a foil mesh is brazed onto the surface. In some cases a retentive feature is lasered onto the surface, these are known as laser-structured bases. Integral brackets are the most common type of bracket fabricated today.

Perforated bases

Perforated bases were one of the first bracket pad designs that allowed the cement to flow freely into and through the holes. Plaque retention and esthetics were its major drawbacks and these bases are no longer used in orthodontics.

Foil mesh bases

An alternative to the perforated base design was the foil mesh. This new base provided a more hygienic surface compared to its predecessor (Maijer and Smith, 1981; Zachrisson and Brobakken, 1978). In addition, it was shown to be more retentive than perforated bases (Lopez 1980, Maijer and Smith, 1981; Zachrisson and Brobakken, 1978).

Foil mesh is attached to the bracket base by welding or brazing. Welding was first used to attach foil mesh to the bracket base. Due to the process of using a high concentrated heat, weld spots used to secure the foil mesh to the bracket appeared to damage the mesh base. The damage decreased the available retentive surface area and as a result reduced the bond strength by obliterating distinct areas of the foil-mesh, leaving sharp areas exposed (Dickinson and Powers, 1980). These sharp areas lead to stress concentrations at the junction of the resin and foil mesh which tended to undermine and weaken the bond. Moreover, weld spots located at the margins were thought to create an area for voids, leakage, and decalcifications (Maijer and Smith, 1981). The welding spurs also prevented the bracket from fully seating. With the invention of laser welding or brazing of the mesh attachment to the bracket, better enamel-adhesive tensile and shear bond strengths could be achieved (Dickinson and Powers, 1980; Maijer and Smith, 1981).

The wire diameter, mesh size, and free volume between the mesh and the base has been shown to affect the penetration of the adhesive resin, escape of air, and the effectiveness of bonding (Maijer and Smith, 1981). The "mesh size" of a foil mesh refers to the number of openings per linear inch and has also been reported to affect bond strength (Thanos et al, 1979). Wire mesh sizes in the range of 60-70 have been shown to provide the optimum bond (Reynolds and von Fraunhofer, 1976; Thanos et al, 1979; Sharma-Sayal, 2003). It has been confirmed that larger mesh spacing (5.1×10^{-2}mm) results in greater bond strength than smaller spacing (2.9×10^{-2}mm) and provides larger spaces for the penetration of the adhesive and the curing light (Wang, 2004).

The size of the mesh wire itself can also affect bond strength. A thinner gauge wire used to fabricate the mesh can result in an intrinsically weaker structure. Reynolds and von Fraunhofer (1976) reported that a coarser mesh led to a more retentive bracket base. The finer mesh may not permit adequate weld strengths between the metal and gauze and the gauze may distort when placed under load. Thus, mechanical interlocking is lost and decreased bond strengths are observed. Reynolds and von Fraunhofer (1976) recommend a mesh wire size of no less than 150 micrometers.

Double mesh designs were fabricated in hopes of increasing bond strength; however a study by Bishara et al (2004) showed similar shear bond strength values and bracket failure modes between the two designs.

Photoetched Bases

Photoetching is the process of placing indentations into the bracket pad. These are usually in the form of small circles. Photoetching has been reported to increase bond strength when compared to perforated bases (Lopez, 1980; Ferguson et al, 1984). However, photoetching has been reported to decrease bond strength when compared to a conventional foil mesh base designs (Lopez, 1980; Maijer and Smith, 1981). The lower bond strength is thought to be caused by the lack of air escape pathways in the photoetched pads, leading to the presence of numerous voids. The presence of air will also result in oxygen inhibition of the polymerization and a layer of uncured resin, further contributing to a weaker bond (Maijer and Smith, 1981).

Integral bases

Integral bases are those that are fabricated as one basic unit. There are three methods used for the fabrication of integral bases: machining/milling, metal injection molding (MIM), and casting. There have been four major groups of retentive patterns: grooved, mesh, waffle, and laser-structured. Some investigators have found integral bases to be more retentive than foil mesh bases (Regan and van Noort, 1989; Sharma-Sayal, 2003), while others have found the opposite (Odegaard and Segner, 1988; Regan and van Noort, 1989; Smith and Reynolds, 1991).

An example of an integral retention groove bracket is the Dyna-lock bracket, 3M Unitek. Several studies have been performed on this machine milled bracket base comprised of shallow milled channels that open at the mesial and distal ends with a "V" grooved pattern running vertically on the surface of the base. In theory, the design should reduce the chance of air entrapment because the excess material is allowed to escape, however, the Dyna-lock bracket has been reported to have lower shear bond strengths than a conventional foil mesh design (Odegaard and Segner, 1988; Regan and van Noort, 1989; Smith and Reynolds, 1991), in part because the shallow channels were shown to be incompletely filled with adhesive. Regan and van Noort (1989) recommended an increase in depth of the milled undercut. The Time bracket by American Orthodontics met this criterion. It is a microetched machined retention groove bracket pad that has been reported to have superior bond strength at 24 hours after bonding compared to several other bracket pad designs including various foil mesh designs (Sharma-Sayal, 2003).

The mesh integral base is a mesh equivalent. Instead of a foil mesh that is attached to a base the mesh pattern is built directly into the bracket base design. Reimann et al (2012) studied the shear bond strengths of various base designs and reported that a mesh equivalent (Carriere) presented with the highest shear bond strength with Transbond XT and Light bond compared to a laser structured base (Discovery) and a foil mesh design (Euro Midi).

The waffle base consists of metallic indentations coming out from the bottom of the bracket. The free volume among the indentations allows for the escape of air and excess resin. Cozza et al (2006) compared a conventional single foil mesh base to the waffle base, grooved base, and lasered base and showed that the waffle base had similar shear bond strengths to the foil mesh and lasered bases.

Laser-structured bases are fabricated from a smooth base. A laser beam is scanned over the base surface, melting and evaporating the metal and burning hole-shaped retentive features into the base. The laser structured Discovery base has been tested against the conventional foil mesh and has been reported to have twice the bond strength (Sorel et al, 2002). Interestingly, unlike many other bracket retention studies, the laser structured base point of failure was located at the enamel-adhesive interface. A failure at the tooth adhesive interface in a dry environment associated with in vitro testing indicates a stronger bond at the bracket-adhesive interface.

With the advent of integral brackets through the process of the MIM'ing and Milling processes, a variety of bracket base designs can be fabricated. Merone et al (2010) tested a novel bracket pad design consisting of concentric grooves of different thicknesses (100 μm and 150 μm). Their rationale for the design was based on a physical principle called the "hydrodynamic analogy". According to this principle, the base was thought to transfer torsional stresses more uniformly to the substrate compared to a conventional mesh base. They reported greater torsional bond strength, lower stress concentrations, and improved stress distribution with lower ARI scores indicating failure at the adhesive-enamel interface for the novel bracket design. The lower ARI scores may lead to an increased possibility of fracture or removal of the enamel. As indicated in previous studies (Knox et al, 2000), the wider grooves showed improvement in adhesive penetration.

Bond strengths of the integral brackets have been shown to improve when a highly filled resin cement is used (Ferguson et al, 1984). It also has been concluded that certain combinations of a bracket and adhesive can perform more optimally than others due to improvements in adhesive and/or light penetration into the base that could promote a more favorable stress distribution (Knox et al, 2000; Reimann et al, 2012).

Bracket pad treatments

Bases can be coated with a porous metal powder, sandblasted, or etched. These treatments increase the mechanical retention by creating small undercuts and/or providing an increase in surface area. Brackets can also be silanated as a final step which creates additional bond strength by producing a chemical bonding between the bracket and the adhesive.

Sintered Bases

Sintering is a method used to create solid objects from powders. Metal injection molding is an example of sintering. A metal powder is injected into a mold and is then heated to sinter the particles to produce a solid object. The mold can contain recesses and/or undercuts to provide mechanical retention. Sintering can also be used to layer a bracket with metal or ceramic particles, creating a porous layer and increasing surface area into which the cement can infiltrate. Smith and Maijer (1983) sintered orthodontic attachments with stainless steel or cobalt-chromium beads of various mesh sizes. They reported a 100% increase in tensile bond strength obtained by the sintered porous metal-coated brackets when compared to a conventional mesh base. In addition, Hanson et al (1983) sintered orthodontic brackets with stainless steel particles that were shown to produce irregular pores up to 100 micrometers. The coating which was 125 micrometer thick was found to provide greater tensile bond strength (88% increase) at the metal-adhesive interface, thus providing better mechanical interlock of the orthodontic adhesive than the foil mesh design.

Sandblasted Bases

Sandblasting, also known as microetching, is the process of propelling fine bits of material, such as aluminum oxide, at high-velocity to etch or abrade a surface. The high velocity is achieved with the use of compressed air. Willems (1997) reported that sandblasting creates micro-roughness that leads to increased surface area for bonding. Retention of foil mesh brackets is significantly enhanced when brackets are microetched or sandblasted prior to bonding (MacColl et al, 1998).

Silanization of bases

Silanization uses a silane molecule dissolved in methanol to promote an increase in wetting of the base and bonding by the adhesive. Siomka and Powers (1985) showed that silanization improved wetting of a conventional foil mesh base, thus allowing penetration of the resin into the mesh undercuts, however the treatment did not appear to promote chemical bonding of the adhesive to the base. The bond strength increased 28% with the silanization of the mesh base. However, they did determine the improvement to be base dependent, as it did not improve the bond strength of the photoetched or integral grooved designs.

Chemically etched Bases

Etching provided by an acidic solution to roughen the surfaces of the bases is known as chemical etching. This preparation is done in order to create a larger surface area for mechanical retention. The etching of an integral grooved design has been shown to increase bond strength by 56% (Siomka and Powers, 1985).

New pad design

A unique bracket design has been developed by Ortho Classic Corporation, with the goal being to produce a bracket pad that will disperse the adhesive in a uniform thickness, to minimize voids, disperse forces evenly throughout the bracket pad, and reduce stress concentrations within the adhesive. The idea was inspired by the tread design seen in many automotive tires. For example, the Power-V tread pattern design of Firestone's Indy® technology rain tires disperses the water to the sides of the tire. The V-shaped pattern allows better water discharge out from under the tire by incorporating a high/low angle approach. In addition to the V-pattern in the center, there are lateral grooves on both sides of the tire's centerline. These lateral grooves pump the water more efficiently through the tread pattern.

Bracket Pad Surface Area

Increased bracket surface area should lead to increased mechanical retention, but with today's demands for more esthetic brackets, the surface area of the brackets have decreased. MacColl et al (1998) found no differences in the shear bond strength of bracket base surface areas between $6.8mm^2$ and $12.4mm^2$ and reported that a bracket base surface area of $6.8mm^2$ was adequate for retention of fixed orthodontic appliances. Cozza et al (2006) also suggested an area of less than $7mm^2$ due to the fact that while the larger surface area of the bracket increases the load carrying capacity, it also causes a reduction in bracket to tooth adaptability.

ORTHODONTIC ADHESIVE MATERIALS

History of adhesive materials

The first bonding agent for restorative dentistry was an unfilled acrylic resin formulated in 1949 by Oskar Hagger, a Swiss chemist working in London. In 1955, Buonocore borrowed techniques of industrial bonding and enhanced bonding to teeth with a phosphoric acid etch for creating irregularities in the enamel surface to enhance mechanical locking. Etching of the enamel surface with a phosphoric acid produces pores 5-6 μm in diameter extending into a depth of 5-25 μm (Reynolds, 1975). The adhesive extends into these pores forming an intimate irregular interface with "resin tags" that produce a micromechanical bond with the enamel. Buonocore's advancement in bonding stimulated efforts to experiment with bonding orthodontic attachments to maxillary anterior teeth.

Bracket adhesive failures due to orthodontic forces and bonding time were early issues. As new adhesives, resin composites, and bonding techniques were introduced to restorative dentistry, orthodontists began to implement them into their practices. In 1962 bisphenol A glycidyl methacrylate (Bis-GMA) resins were introduced and later applied to orthodontic practice. Bis-GMA creates an extremely rigid polymer with less shrinkage, greater strength, and less water absorption than acrylic resins. Resin composites are composed of Bis-GMA and other dimethacrylate monomers, a filler material such as silica, and a photoinitiatior such as comphorquinone. In 1977 Concise Ortho Adhesive, a two paste, chemical cure adhesive system became the first specific orthodontic adhesive formulation. Since then improvements have been made in resin composites which include no-mix adhesives and light activated direct bonding materials.

The two major adhesive systems which are used in the direct bonding of orthodontic brackets today are resin-based luting cements and resin reinforced glass ionomer cements. Much attention has been given to resin reinforced glass ionomer cements because of the potential to create a cariostatic effect due to fluoride release, the fact that they do not require any acid conditioning, and a lessened moisture sensitivity as compared with resin-based cements. However studies have demonstrated a lower bonding strength as compared to resin containing luting cements. The most widely adopted bonding system in contemporary orthodontics is the acid-etch-resin composite technique.

Thickness of adhesive

An even adhesive thickness will allow for a pre-adjusted appliance to properly express the three dimensional position of a tooth. An imperfect adaptation of the bracket base to the tooth will not only effect the final tooth position, but also will result in a uneven thickness of adhesive under the bracket base that will likely play a role in the bond survival. A minimal and uniform thickness of resin cement has been recommended for maximum strength in the bonding of orthodontic attachments to teeth (Zachrisson and Brobakken, 1978).

Increased thickness of adhesive has been reported to weaken the joint. Thicker layers are subject to increased polymerization shrinkage that can create internal stresses in the material that act tangentially to the bracket-adhesive interface, and can introduce imperfections such as cracks and voids in thicker layers that can lead to an uneven distribution of mechanical stresses resulting in stress concentrations (Buonocore, 1963). A bond failure within the adhesive also can occur when film thicknesses are increased due to an incomplete polymerization of the cement between the tooth and the bracket (Evans and Powers, 1985). Jost-Brinkman et al (1992) reported that a light-cured resin cured adequately in a layer of 0.2mm or less and did not cure in greater thicknesses. The results indicate that light cured adhesives achieve maximum bond strength at 0.2mm. Schechter et al (1980) also reported that with increasing thickness up to 0.75mm the shear bond strength is decreased, but he reported no changes in tensile bond strength. Evan and Powers (1985) reported that with Concise, a two paste self-cure adhesive system, there was a gradual decrease in tensile bond strength as cement thickness increased from 0.25mm,0.30mm, 0.33mm, 0.38mm, to 0.51mm.

According to the Beam Theory, the further the applied force is to the bonding interface the greater the moment produced on the bracket. This concept supports the research reported above. However, more recently, Arici et al (2005) reported that although tensile bond strengths decreased, mean shear bond strengths of a light-cured resin composite progressively increased when the adhesive thickness increased from 0 to 0.25 to 0.5mm. They used finite element modeling to explain this, showing that it is impossible to apply a pure shear load to a bracket because of an unavoidable inherent bending moment. Arici et al (2005) believe that simpler uniform cross-section beam concepts are not necessarily applicable to the tooth-bracket system because of its geometric complexity.

Force Required for Adequate Adhesive Layer

Previous studies have shown that adhesive thickness affected the bond strength, but this depends on the type of adhesive material and bonding test used (tensile vs. shear bond strength tests). The force applied by the operator and the amount of adhesive affect accurate bracket positioning and the bond strength. Muguruma et al (2010) studied the force applied to bond a bracket and the relationship this has with the amount of adhesive used. They reported that when 12 orthodontists placed brackets directly in vitro, the application force obtained ranged from 53 to 940 grams (mean= 340g, median=245g). They evaluated the adhesive dispersion under the bracket at application forces of 100, 200, and 300 grams. It was reported that with forces of 100 and 200g there was an insufficient amount of paste to fill the entire bracket base area and that a force greater than 200g might be preferable for achieving a thin resin composite layer and avoiding an insufficient amount of resin composite paste on the bracket base.

Adhesive-Bracket Material Combination

Bracket base morphology can influence the strength of the bracket cement interface by determining the geometry (depth, size, and distribution) of the resin tags and the penetration of light and the polymerization of light activated materials (Knox et al, 2000). The differences in base design can have differing stress distributions within the adhesive-bracket interface. It is also possible that different adhesive properties, such as viscosity, can influence an adhesive's penetration into the bracket base which can also affect the mechanical retention of the bracket base.

Knox et al (2000) studied combinations of various adhesives and bracket base designs. In the study, it appeared that certain combinations of brackets and cements performed optimally. For example, it was found that a single mesh base (60, 80, 100) performed well in the shear bond strength tests with Right-On and Concise (Chemical cure adhesives), 11.88-22.72MPa, and other than the 80-mesh bracket, performed relatively poorly with Transbond (Light cure adhesive), 2.18-5.15MPa. The Dyna-Lock (integral grooved based design) and Minitwin (integral waffle base design) performed fairly well with all the cements, 8.87-17.16MPa. The double mesh base performed well with Right On, 13.75MPa and reasonably well with Concise, Transbond, and Fuji Ortho LC, 6.0-9.2MPa.

Reimann et al (2012) also reported significant differences in shear bond strength in various material combinations. It was reported that all combinations of brackets and adhesives were clinically acceptable 12.3-17.2MPa, however the highest bond strength combination was seen with Carriere, a milled mesh-equivalent base, and Transbond XT (17.2±3.2 MPa) and the lowest was Euro Midi, foil mesh base, and Phase II Chemical Cure adhesive (12.3±2.8MPa).

Light-Cure Adhesive

Resin composite can be highly filled (60-80%) or lightly filled (28%) depending on the weight of silica or glass filler. Highly filled resins have been shown to bond better to metal brackets (Dickinson and Powers, 1980). An increase in filler content also increases the resins viscosity, which is preferred by some clinicians as it prevents slippage of the bracket on the enamel surface. Resin composites are available in auto-polymerizing, photo-polymerizing, and dual cure systems. Light cure adhesive resin is the most commonly used today for the direct bonding of orthodontic brackets. Unlike a two-paste system, it is not as time sensitive and allows the clinician ample time for accurate bracket placement and removal of excess cement. There are several options of light cure adhesive resins on the market and several studies have performed comparing different types of light cure adhesive. Reimann et al (2012) showed similar bond strengths for two light cured resin composite adhesives and a foil mesh bracket, Euro Midi, Transbond XT (16.1±3.7MPa) and Light Bond (16.3±5.1MPa). Flores et al (1999) also showed similar bond strengths of two light cured adhesives, Transbond (14.7 ± 4.22MPa) and Fuji Ortho LC (15.8 ± 2.08 MPa).

Transbond XT is a BIS-GMA based, no mix light cured highly filled resin composite and is a standard product in current clinical orthodontics and has been a component of many comparative adhesion studies. The range of bond strength has varied within the literature with mean shear bond strengths of 9.15 ± 1.65MPa/ORMCO Mini Diamond Double Foil Mesh bracket (Iijima et al, 2007), 10.4 ± 2.8MPa/3M Victory Foil Mesh bracket (Bishara, 1999), 5.8 ± 2.8/3M Victory Bracket and 5.2 ± 3.9/Innovation Double Mesh Bracket (Bishara, 2004). 3M Unitek has reported a mean bond strength of Transbond XT to be 15 ± 5MPa with Victory brackets when bonded in a dry environment.

Light Curing Time

In orthodontics, the adhesive makes a micromechanical bond with the enamel as "resin tags", and must also flow into the undercuts of a bracket base forming a second interface with a micromechanical bond. To form these micromechanical bonds within the enamel and the bracket pad, the adhesive must go through a polymerization process that is typically initiated by visible light.

Blue light with wavelengths between 410 and 500 nanometers are necessary for resin polymerization since camphorquinone, the usual component of photoinitiation systems for dental materials, has its absorption maximum in this range (467nm). The goal of bonding orthodontic brackets to the teeth is to maximize the polymerization of the composite, thus enhancing the cross-linking of the polymers chains. There are two groups of units that make blue light producing technologies. The first group produces "white light" that is filtered to the range of the blue light: Quartz tungsten halogen

(QTH) and the plasma arc (PAC) polymerization units. The second group comprises "blue light" curing devices that produce blue light directly: Laser and light emitting diodes (LED).

Several suggestions have been made for the direction and amount of light curing in order to maximize bond strength at the bracket-adhesive interface. Some recommend curing occlusally down the long axis of the tooth as close as possible to the bracket-adhesive interface, as well as additional cure time directed from either mesial, distal or gingival to maximize polymerization. Other studies have suggested directing the light from the lingual surface to take advantage of transillumination. MacDonald (2005) studied different light curing protocols (LED and QTH) and compared the bond strength of MBT Victory brackets bonded with Transbond XT. It was reported that curing with the LED unit (825 nW/cm^2) produced bond strength values that were statistically similar to the QTH unit (515 mW/cm^2) in half the time. The LED unit (5 sec Mesial and 5 sec Distal) produced a mean shear bond strength of 6.81 MPa compared to the QTH unit (10 seconds Mesial and 10 seconds Distal) that produced a mean shear bond strength of 6.30 MPa. Increasing the curing time did not affect the LED bond strength, but did significantly increase the QTH bond (15 sec Mesial, 15 sec Distal) with mean shear bond strength of 8.46 MPa. It was also reported that curing from the mesial and distal produced significantly greater bond strengths than from the occlusal alone with the LED unit. Adding additional curing from the occlusal surface rather than just curing from the mesial and distal surfaces did not have any significant effect on bond strength for either light source.

3M unitek recommends 10 seconds of curing time with their Ortholux LED curing light (5 seconds Mesial and 5 seconds Distal). The manufacturer reports an irradiance of 1000 mW/cm^2, however as stated in MacDonald (2005) when using a handheld radiometer, the irradiance was reported to be only 825 mW/cm^2 in their study.

Degree of resin conversion

The extent of light-cured monomer polymerization is dependent on several factors: exposure time, photoinitiator concentration, light intensity emitted from the curing unit, and the background reflectance. The importance of the curing efficiency on the performance of resin composites has been well established in the literature. For instance, it has been shown that mechanical properties, such as flexural modulus of elasticity, tensile strength, and compressive strength, depend on the degree of cure of the resin matrix (Ferracane and Greener, 1986). Other properties of the adhesive, such as solubility and degradation are also strongly correlated with the degree of cure (Eliades, 2006). More recently, the biocompatibility of uncured resin has been a subject of study. Monomer leaching can result from an insufficiently dense network brought upon by a decreased conversion of double bonds. The release of such substances has been thought to possibly inflict biologic effects. It has been shown that a moderate reduction in periodontal ligament fibroblast DNA synthesis was obtained from both chemically and light-cured adhesives with a degree of cure of 52% and 47%, respectively (Gioka et al, 2005). This may imply a minor cytostatic effect which may suggest a biologic concern with uncured resin.

To determine the degree of resin conversion (DC), a test is done to measure the conversion of monomer into polymer with the use of Fourier-Transform Infrared Spectrophotometry (FTIR). More specifically, comparing the conversion of double bonds (C=C) into simple carbon bonds (C-C). Ideally, an adhesive resin should have all of its monomer converted to polymer during polymerization. However, recent studies have shown that when resin composite (Transbond XT) discs were prepared and tested with FTIR, the degree of conversion ranged from 24-47% depending on the type of cure unit and amount of curing time. For example, Cerveira et al (2009) compared Quartz Tungsten Halogen light (QTH) to a Light emitting diode (LED) curing unit and reported DC for Transbond XT to have a range of 43-46% with the QTH and 39-47% for the LED light, with the range given by varying the curing times, 10-30 seconds for the QTH and 5-15 seconds for the LED. In addition, Berthold et al (2011) reported a DC that also ranged from 43-46% with a Quartz Tungsten Halogen (QTH) light curing unit and 24-33% with a Plasma Arc (PAC) curing unit when subjected to a range of cure times, again with the range varying with the curing times, 10-30 sec for the QTH and 1-3 seconds for the PAC.

Clinically, polymerization of an adhesive under a metal bracket depends on the ability of the light to penetrate the resin material, as well as, the amount of light scattered from the background surface (Fan 1984). It has also been shown that when bonding steel brackets with a light-cured orthodontic adhesive, an even lower DC results with in the resin composite, Transbond XT control showed a DC of 54.7% versus 32.4% under the metal bracket (Shinya et al, 2009). A considerable amount of DC variation may occur under orthodontic brackets because of the difficulties in irradiating the adhesive evenly from each side of the bracket, as well as, variation in bracket base designs that may present a difference in light penetration and scatter.

ORTHODONTIC BOND STRENGTH

Tests

There are three modes of force application to test for bond strength: Tensile, torsion, and shear. Tensile test can be done with a testing machine with a wire dislodging loop, torsion can be tested with customized wrenches, and shear bond strength can be tested with the movement of a bar against a mounting jig. Shear bond strength is the most accurate clinical simulation of a bracket debonding. Occlusal forces, such as a food bolus or opposing occlusal tooth interference, produce forces to the archwire or directly to the bracket. This is the most common cause of a bracket debond.

It is likely that the fracture, during loading, starts at a weak point in the system, usually a surface defect such as a void or crack, or at the border of the bracket (Higgs et al, 2001). Cement is brittle and these initial cracks lead to complete fracture and debonding of the bracket.

Algera (2010) evaluated brackets bonded with Transbond XT and compared their tensile strength to their shear bond strength. It was reported that the lowest bond strength values were observed with the tensile test, while shear tests resulted in significantly higher bond strength values. It was also observed that the shear bond strength was higher when the load was applied to the short side as compared to the long side because the highest stress concentrations are located on the side at which the load is applied. Clinically most forces are applied to the long side of the bracket by a food bolus or occlusal interferences.

Fractures are initiated at peak stress locations. As a consequence, the surface area of the bracket pad is not predictive of bond strength; rather the bracket pad design and mode of loading may be more relevant (Algera, 2010).

Bond strength vs. force

The values of strength can be measured in force [Newtons (N)] per unit area (mm^2) and is most often reported as strength [MegaPascals (MPa= N/mm^2)], which is calculated by dividing the force at failure by the bonding area. One kilogram of force is equal to 9.8N.

Shear bond strength over time

It has been shown that shear bond strength for various bracket types increases over a 24 hour period (Sharma-Sayal et al, 2003). However, when a biomaterial is exposed to the oral cavity over a period of time there can be a modification of surface and structural properties of the material that might have effects of the longevity of the bond strength (Eliades and Bourauel, 2005). This concept is known as aging of polymeric adhesives. This aging effect is multifactorial which can include pH fluctuation, complex cyclic loading, microbial attack, and enzymatic degradation. Oesterle and Shellhart (2008) reported that the shear bond strength of orthodontic brackets increases from 30 minutes (15Mpa) to 24 hours (21MPa) and then tends to decrease over the next 24 months (12MPa) when brackets were aged in distilled water at 37 degrees Celsius. The long term effect of water immersion on bond strength was shown in this study and is thought to be further compounded by other factors in the oral environment.

Clinically acceptable shear bond strength

In the orthodontic bond, there are two requirements: it must be sufficient to retain the brackets, but also low enough to allow for easy bracket removal and adhesive clean-up. Forces subjected to an orthodontic bracket throughout treatment are applied to the bracket-cement-enamel system primarily by orthodontic forces and occlusal loading. Fields et al (1986) studied vertical occlusal forces in children, adolescents, and adults and reported a range of average chewing forces to be 7 to 16 kg and maximum biting forces for the groups to be in the region of 15 to 30 kg. It is difficult to determine the mean strength required of an adhesive, since not only do occlusal loads vary enormously, but an assessment of the proportion of these forces transmitted to the bonded attachment is necessary (Reynolds, 1975). Algera et al (2010) has reported that the stress distribution over the bracket-cement-enamel system is not homogenous during loading using a finite element model. Fractures are initiated at the peak stress locations and it was shown that the peak stress under the bracket in the finite element model was reported to be much higher than the actual calculated shear bond strength of the bracket, once again verifying that the forces under the cement-bracket interface is non-homogenous and complex.

It has been suggested that the bond strength of 6-8 MPa is clinically effective for orthodontic bonding (Reynolds, 1975). This suggestion was most likely made as a requirement to withstand forces enough to produce orthodontic tooth movement under normal mechanotherapy and occlusal loading. According to Eliades and Bourauel (2005), Reynolds (1975) proposed value of 6-8MPa does not take into account the stresses developed during the mastication of hard foods or higher chewing velocities nor does it include the aging factor of the polymeric adhesive and associated environmental stress fatigue phenomenon. However, even though the bond strength is "clinically effective" it does not mean that debonding will not occur with Transbond XT's average shear bond strength of 15MPa, as suggested by the manufacturer. In addition, it is important to note that this mean was calculated in a dry environment. The oral environment is very different and saliva contamination was reported by Iijima et al (2007) to reduce the Transbond XT shear bond strength from 9.15±1.65 in a dry environment to 1.47±0.93 in a wet or saliva contaminated environment. Clinically acceptable bond strength recommendations are a minimum requirement, adhesive and bracket combinations that surpass this recommendation will only improve the chances of withstanding maximum occlusal forces.

Bracket Bond Failure Rates

A clinical bond failure rate of 17.87% with a mean survival time of 235 days has been reported with the use of a chemical cure adhesive, Unite, over an 18 month period (Bherwani et al, 2008), 16%

for a chemical cure adhesive, Right-on, and 23% failure rate with a light-cured adhesive, Heliosit-orthodontic, over an 18 month period (Lovius et al, 1987), and a 6% overall bond failure rate with a mean survival time of 442 days with a light cured resin, Transbond, over a 5 year period (Millet et al, 1998). Bond survival has been reported to vary significantly between tooth types, with more failures reported in the buccal segment than the labial segment (Newman, 1978; Lovius et al, 1987; Linkletter and Gordon, 2003; Millet et al,1998; Berwani et al, 2008). Mixed results have been reported in the failure between dental arches with some reporting more failure in lower arch than the upper (Newman, 1978; Lovius et al, 1987; Linkletter and Gordon, 2003) and others reporting no differences in bond failure between arches (Millet et al, 1998; Berwani et al, 2008). The mean time between bonding and time of failure has been shown to be as low as 245 days or 8 months (Bherwani et al, 2008) with a chemical cure adhesive and as high as 442 days or 15 months (Millet et al, 1998) with a light cure adhesive.

Site of bond failure

In order to maintain the integrity of the enamel, ideally the site of bracket failure should occur at the bracket-adhesive interface. The adhesive would mainly remain on the tooth and should be carefully removed by the orthodontist. The mode of failure can be defined as cohesive or adhesive and is represented in the Adhesive Remnant Index (ARI) developed by Artun and Berglund (1984):

ARI "0"= 0% adhesive on the tooth or 100% adhesive on the bracket

ARI "1"- under 50% of the adhesive remains on the tooth or over 50% adhesive remains on the bracket.

ARI "2"- over 50% of the adhesive remains on the tooth or under 50% adhesive remains on the bracket

ARI "3"- 100% of adhesive remains on the tooth or 0% of the adhesive remains on the bracket

Cohesive failure is a failure within the adhesive in which case the adhesive would be on both the tooth and bracket. Adhesive failure is when the fracture occurs between the adhesive and either the tooth or the bracket. The ARI provides information on the weakest part of the bonding system. If the stronger bond is at the bracket-adhesive interface, the majority of the composite stays on the bracket. Some advantages of this would be an easier and quicker debonding procedure with little to no resin tags left behind in the enamel, but the major disadvantage is a risk of an enamel lesion. Conversely, if the stronger bond is at the tooth-adhesive interface, the majority of the composite stays on the tooth. If the weak bond is located at the bracket-adhesive interface, more cleanup is necessary, but there the enamel is left intact. Algera (2010) showed a shear bond strength test fracture pattern of Transbond XT that starts as an adhesive fracture at the cement-bracket interface and then changes into a cohesive fracture. If the tooth is prepared properly, in the absence of oral contamination, the failure site of metal brackets has been identified as the bracket-adhesive interface (Reynolds and von Fraunhofer, 1976; Faust et al 1978, Dickson and Power, 1980; Regan and van Noort, 1989; Jost-Brinkmann et al, 1992; Eberhard et al, 1994; Bishara et al, 1999, Arici et al, 2005).

Factors affecting bracket retention

There are several factors that can affect the bond success of the orthodontic bracket. The oral environment can produce a host of different clinical situations that can affect the bond. Alterations in enamel (decalcifications and/or enamel hypoplasia), saliva contamination during bonding, aging of the polymeric adhesive over time, and/or variations in dental anatomy that may impede the even seating of the bracket base can be causes of bond failure. Clinically, it is more difficult to manage moisture control in the posterior segment. As outlined above the tooth type and dental arch are also a factor. There have been several studies that have shown that the type of bracket base, the adhesive and primer materials chosen for bonding, the combination of adhesive and bracket base used, as well as, the bonding and light curing technique employed can affect bond strength. The patient's diet can also contribute to bond failures. There are several factors that are out of the control of the clinician, but those that can be controlled may increase the bond strength of the orthodontic bracket and in turn increase treatment efficiency by saving time for both the patient and the clinician.

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