Combinations of etchants, composite resins, and bracket systems: An important choice in orthodontic bonding procedures

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Abstract: The objectives of this investigation were: (1) to compare the shear bond strengths (SBS) of metal, ceramic, and plastic brackets using different concentrations of maleic and phosphoric acid gels and aqueous solutions, and (2) to determine if a relationship exists between the type of acid etchant and the location of resin after debonding. A sample of 210 bovine incisors was divided among three different bracket groups (Victory series metal, Transcend 6000 ceramic, Spirit MB plastic). Prior to bonding, enamel was acid-etched using 37% phosphoric acid (H_3PO_4) gel and aqueous solution, 10% maleic acid gel and aqueous solution, 10% H_3PO_4 gel and aqueous solution, or 2% H_3PO_4 aqueous solution. SBS testing and the adhesive remnant index (ARI) score provided insight into the effects of the bonding process on enamel. Resin tags associated with each etchant type were inspected under scanning electron microscopy (SEM). Statistical analyses (level of significance, p=0.05) of the data showed significant differences among groups. It was concluded that specific acid-composite-bracket combinations are recommended for use in clinical orthodontic practice in order to achieve efficient bonding.

Key Words: Orthodontic bonding, Acid concentrations

Orthodontic bonding of brackets has become a widely accepted clinical procedure.[1] A demand also exists for more esthetic appliances.[2] Early esthetic brackets were composed of polycarbonate,[3] but their inability to adequately withstand torsional forces and distortion from water absorption limited their use.[4] Ceramic brackets were introduced in 1986; unlike the earlier polycarbonate brackets, they resisted staining and were chemically inert to oral fluids.[5] Debonding of ceramic brackets, however, led to undesirable complications, including enamel fractures, cracks, and flaking.[2]

The three factors that affect the strength of the bond between the bracket and the enamel surface are the bracket base retention mechanism, the adhesive material or bonding resin, and the preparation of the tooth surface. In the case of metal brackets, it has been shown that foil-mesh of 60- to 70-gauge seems to provide the strongest bond, and that foil-mesh bases are preferable to perforated bases.[6,7] Sandblasting or micro-etching of foil-mesh bases has also been shown to produce superior shear bond strength.[8] The bond strength of polycarbonate brackets was shown to be improved by the addition of metal slots and ceramic fillers, although problems with durability, distortion, and staining have limited their clinical application.[4,9,10] On the other hand, ceramic brackets have been shown to exhibit significantly higher bond strengths than metal brackets,[11-14] particularly when the base is chemically rather than mechanically attached to the bracket.[15]

Filled and unfilled acrylic and diacrylic resins have been used for bonding brackets to teeth. It has been shown that the cross-linking found in diacrylic resins together with their filler content contributes to their greater strength and reduction in polymerization shrinkage.[16] The filler particles may be large (macrofilled) or small (microfilled), and the resins may be photo-cured, auto-cured, or dual-cured. In the latter case, they are initially photopolymerized, then left to autopolymerize to reach their final set. New materials, such as fluo-

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Submitted: February 1998, **Revised and accepted:** October 1998

Angle Orthod 1999;69(3):267-275.

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ride-releasing adhesives[17] and photo-cured glass ionomer cements, have recently been introduced.[18] Increasing the filler content of resin adhesives has produced equivocal results with respect to increasing the shear bond strength of brackets to enamel.[13,14,19,20] It appears from these and other investigators' results that specific adhesives should be appropriately matched to specific brackets.[16,21]

Acid conditioning of the enamel surface to enhance the retention of resin was first introduced by Buonocore (1955).[22] Acid conditioning changes the enamel surface from a low-energy hydrophobic surface to a high-energy hydrophilic surface, resulting in increased surface tension and wettability.[4] In general, liquid or gel preparations of orthophosphoric acid in concentrations ranging from 2% to 85% have been used to condition tooth enamel prior to bonding of orthodontic brackets.[23-27] Although a range of 15 to 90 seconds has been reported, acid conditioning for 15 seconds is recommended.[4,5,28-32] Other conditioning procedures have included the use of maleic acid,[8,33,34] and conditioning by inducing crystal growth on the enamel surface.[35-38]

The purpose of the present study was: (1) to measure and compare the shear bond strengths of metal, ceramic, and ceramic-reinforced polycarbonate brackets using different concentrations of maleic and phosphoric acid gels and aqueous solutions, (2) to determine if there is a difference between gels and aqueous solutions, and (3) to observe the location of the resin after debonding, its relationship to the type of conditioner, the bond failure interface and resin location, and what damage occurred to the enamel surface following debonding.

Table 1
Acid conditioners used in this investigation

Etchant	Abbreviation	Source
37% Phosphoric acid gel	(37Pg)	Reliance Orthodontic Products Inc, Itasca, Ill
37% Phosphoric acid solution	(37Ps)	BDH Inc, Toronto, Ontario, Canada*
10% Maleic acid gel	(10Mg)	Scotchbond Multi-Purpose, 3M Co, St. Paul, Minn
10% Maleic acid solution	(10Ms)	BDH Inc, Toronto, Ontario, Canada**
10% Phosphoric acid gel	(10Pg)	Clinical Research Dental, London, Ontario, Canada
10% Phosphoric acid solution	(10Ps)	BDH Inc, Toronto, Ontario, Canada***
2% Phosphoric acid solution	(2Ps)	BDH Inc, Toronto, Ontario Canada****

*31.8 ml. 85% orthophosphoric acid to 100 ml distilled water
*10 g. maleic acid crystals to 100 ml distilled water
**7.4 ml 85% orthophosphoric acid to 100 ml distilled water
***1.41 ml 85% orthophosphoric acid to 100 ml distilled water

Table 2
Mean shear bond strengths (MPa) of each acid conditioner for each bracket type

Etchant	n	Metal (n=70) Mean ± SD	Transcend (n=70) Mean ± SD	Spirit (n=70) Mean ± SD
37% H_3PO_4 gel (37Pg)	10	10.87 ± 2.31	10.67 ± 1.94	6.88 ± 1.51
37% H_3PO_4 solution (37Ps)	10	14.01 ± 2.11	10.36 ± 1.07	6.45 ± 0.56
10% Maleic gel (10Mg)	10	13.21 ± 1.96	10.16 ± 1.53	8.05 ± 1.05
10% Maleic solution (10Ms)	10	13.86 ± 2.62	9.47 ± 1.34	6.97 ± 1.05
10% H_3PO_4 gel (10Pg)	10	12.83 ± 1.83	12.13 ± 1.51	7.81 ± 0.62
10% H_3PO_4 solution (10Ps)	10	13.11 ± 2.70	9.44 ± 1.42	6.48 ± 0.55
2% H_3PO_4 solution (2Ps)	10	8.11 ± 2.51	8.17 ± 0.78	6.54 ± 1.16

Materials and methods

Teeth

A total of 210 bovine incisors were prepared for experimentation.[8]

Brackets

Three types of brackets were bonded to enamel in this study: a metal bracket (Victory Series, 3M/Unitek Corp, Monrovia, Calif) with an 80-gauge woven mesh mechanical retention base; a polycrystalline aluminum oxide ceramic bracket (Transcend Series 6000, 3M/Unitek Corp, Monrovia, Calif) with a microcrystalline bonding surface for primarily mechanical retention; and a polycarbonate bracket reinforced with ceramic filler (Spirit MB, Ormco Corp, Glendora, Calif) containing a stainless steel slot and a mechanical retention base. The bracket groups are identified as metal, Transcend, and Spirit, respectively. Maxillary central incisor brackets were used because of their relatively flat bases. A morphometric computer program (Digitek Image Processing System, series 100, Digitek Co, Brooklyn, NY) was used to calculate the base surface area of 10 randomly selected brackets of each group (metal, 10.84 ± 0.35 mm^2; Transcend, 11.37 ± 0.22 mm^2; Spirit, 11.61 ± 0.35 mm^2).

Bonding resin

Bonding, using an autopolymerizing two-paste, highly (72%) filled resin of 0.3 mm silica particle glass (Phase II system, Reliance Orthodontic Products Inc, Itasca, Ill) was preceded by conditioning of the enamel surface.

Conditioning agents

The conditioning agents used in this study were aqueous solutions of phosphoric (2%, 10%, and 37%)

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and maleic (10%) acids, and their respective commercially available gels (Table 2). Groups of 10 teeth were conditioned with each of the seven acid conditioners, and 10 brackets of each of the three types were used, for a total 21 groups (210 teeth).

Embedding and surface preparation

The teeth were embedded in autopolymerizing polymethyl methacrylate cylinders (PMMA, Esschem Co, Penn). Care was taken during embedding to ensure that the labial surface of each tooth projected above the level of the PMMA and was parallel to the horizontal plane. The labial surface was then flattened on a water-irrigated grinding wheel using #180 grit SiC paper. In order to preserve the material prior to use, the samples were stored in distilled water at 4°C prior to bonding.[8]

Bonding the brackets

Groups of 10 embedded teeth were removed from water storage and treated according to the protocol outlined in Table 1. The previously flattened enamel surface was reground using #600 grit SiC paper on a water-irrigated grinding wheel in order to remove any superficial surface film that may have developed during the 4- to 6-week storage period. Each tooth was rinsed in distilled water and dried with an electric hair dryer (Prostyle 1500, Sunbeam Corp, Canada Ltd) prior to acid conditioning of the enamel surface for 20 seconds. The conditioner was applied to the enamel surface using either a brush (for gels) or a cotton pledget (for aqueous solutions). The surface was then washed with distilled water for 20 seconds and dried with the hair dryer for 30 seconds.

The bracket was bonded to the enamel surface using Phase II adhesive, which was applied to the bracket base in accordance with the manufacturer's instructions. The bracket was then placed on the conditioned enamel surface and seated using a constant force as applied by a guiding pin from an articulator.[8] This was done to ensure that the bracket was seated under a constant force and, at the same time, allowed the investigator to remove excess resin from around the bracket base with a dental explorer without interfering with the polymerization process. After bench curing for 5 minutes, each specimen was placed in a container of distilled water and stored for 7 days at a temperature of 37°C. To inhibit bacterial growth during storage, thymol crystals were added.[39]

Shear bond strength testing

Following storage for 7 days, each specimen was clamped in a universal testing machine (Instron Model 4301, Instron Corp, Canton, Mass) with the flattened enamel surface perpendicular to the horizontal plane. A sharpened chisel blade was placed in contact with the incisal aspect of the bracket standoff and, using a load cell of 100 Kg and a crosshead speed of 1.5 mm/min, the bonds were tested to failure. Shear bond strengths were recorded in megapascals (MPa).

Resin location

Debonding of the brackets was followed by examination of the corresponding enamel surfaces under a light microscope using a magnification of x35. The four-point adhesive remnant index (ARI)[38] was used to assess the amount of resin composite that remained on the enamel surface. Both the embedded incisor and its detached bracket were then stored in the original container to allow preservation of the specimen prior to preparation for SEM examination.

Scanning electron microscopy

The debonded teeth were removed from the embedding PMMA. The teeth and their companion brackets were dehydrated in absolute alcohol for 1 week and then allowed to air dry for 1 hour. They were then mounted on scanning electron microscopy (SEM) stubs in such a way that the enamel surface and bracket base could be viewed, and then sputter-coated with 3 nm of platinum in a Polaron E5100 coating unit (Polaron Equipment Ltd, UK). In addition, one unbonded specimen of each of the three types of brackets was also prepared in a similar manner for the SEM (Hitachi S-2500, Hitachi, Mito City, Japan). All specimens were examined under SEM at an operating kilovoltage of 10 Kv, using magnifications that best illustrated the area under investigation.

Statistical analysis

The mean shear bond strengths and standard deviations were calculated and recorded for each group. The data were statistically analyzed using a two-way analysis of variance (2-way ANOVA) to determine whether there was any difference between each bracket type and the different conditioners. Multiple pairwise comparisons were done using Bonferroni's correction of Student's *t*-test. The level of significance for all tests was p=0.05. The statistical analysis was done using the Statistical Analysis System (SAS 6.04, Cary, NC).

Results

Shear bond strengths

The mean shear bond strengths and standard deviations for each bracket type and acid conditioner used in this study are portrayed in Table 2. It was noted that the overall mean shear bond strengths for metal and Transcend brackets were higher than those recorded for the polycarbonate Spirit brackets. The within-bracket statistical comparisons were carried out to assess whether there were any differences between (1) phosphoric and maleic acid conditioners, (2) aqueous and gel preparations, or (3) differing concentrations of phosphoric acid. The results showed that, for each of the three bracket types, there were no statistically signifi-

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cant differences (p>0.05) in mean shear bond strength between 10% phosphoric and maleic acid gel or between phosphoric and maleic acid aqueous conditioners (Figures 1, 2, and 3). With the exception of Transcend brackets, where 10% phosphoric acid gel showed a statistically higher mean shear bond strength than its aqueous counterpart (p>0.05), there were no significant differences between the respective 37% and 10% phosphoric and maleic acid gels and solutions.

The results showed that, for metal and Transcend brackets, the concentration of phosphoric acid conditioning agents had some statistically significant effects on mean shear bond strength. In the case of metal brackets, a 2% phosphoric acid solution produced a mean shear bond strength that was significantly lower (p>0.05) when compared with 37% and 10% phosphoric acid solution or its 10% gel (Figure 1). There was, however, no statistically significant difference in mean shear bond strength between the 2% phosphoric acid solution and its 37% gel counterpart. For Transcend brackets, the 2% phosphoric acid solution showed a statistically significant mean shear bond strength (p>0.05) when compared with 37% and 10% phosphoric acid gels and the 37% solution (Figure 2). The Transcend group also showed no statistically significant difference in mean shear bond strength between the use of 2% and 10% phosphoric acid solutions. In general, the 2% phosphoric acid solution produced statistically lower mean shear bond strength for both metal and Transcend brackets when compared with the other phosphoric acid gels and solutions (Figures 1 and 2). In the case of Spirit brackets, there were no statistically significant differences in mean shear bond strengths for any concentration of phosphoric acid solution or gel (Figure 3).

The adhesive remnant index (ARI)

In order to assess whether the type of conditioning agent had any effect on the ARI score,[38] the number of observations under each parameter of the index was recorded together with the mean shear bond strength applicable to the number of observations that were recorded under that parameter (Tables 3, 4, and 5). The results showed that there were minimal differences in ARI scores between phosphoric and maleic acid conditioners for all three bracket types. Similarly, there were minimal differences when comparing gels and solutions. Interestingly, only two enamel fractures were recorded, and these were in the metal bracket groups with 37% phosphoric and 10% maleic acid solutions.

The results indicated that the concentration of phosphoric acid conditioners had an effect on ARI scores for both metal and Transcend brackets. In the case of metal brackets, higher concentrations of phosphoric acid (37% and 10% vs. 2%) tended to show higher ARI scores (Table 3). For example, brackets bonded with 2% phosphoric acid used as the conditioner debonded with an ARI score of zero. For Transcend brackets, following conditioning with 37% and 10% phosphoric acid, ARI scores of 2 and 3 predominated, whereas the 2% solution showed scores of either 0 or 1 (Table 4). In general, for metal and Transcend brackets, the 2% aqueous phosphoric acid conditioner produced lower ARI scores than 37% and 10% solutions and gels. In the Spirit bracket group, minimal differences existed in ARI scores for phosphoric and maleic acid gels and solutions, although it should be noted that the scores were consistently high in this group (Table 5).

There appears to be no evident relationship between the ARI scores and the mean shear bond strengths (Tables 3, 4, and 5).

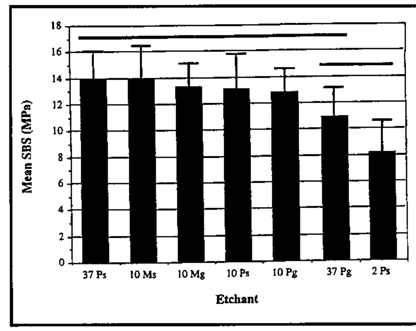

Figure 1
Comparison of mean shear bond strengths with each acid conditioner for metal brackets

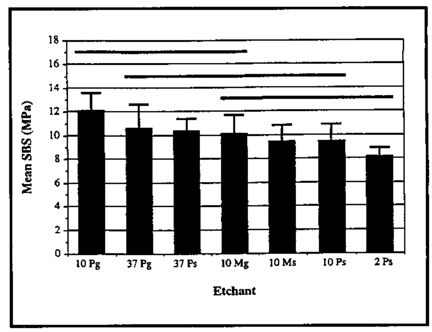

Figure 2
Comparison of mean shear bond strengths with each acid conditioner for Transcend brackets

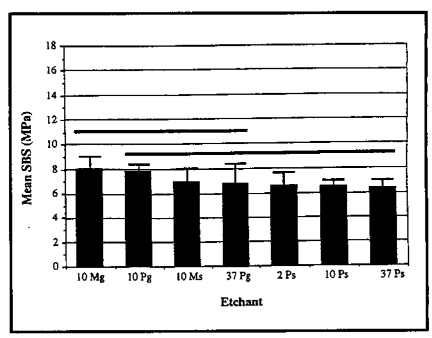

Figure 3
Comparison of mean shear bond strengths with each acid conditioner for Spirit brackets

Relationship of bracket type to conditioner

It was noted that, in the case of metal brackets, 72.8% of the samples debonded with an ARI score of 0; the mean shear bond strength of this group ranged from 8.11 to 13.73 MPa (Table 3). The results indicated that 10% phosphoric and 10% maleic acid solutions and gels fulfilled

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these criteria, and the mean shear bond strength exceeded 13.00 MPa. The 2% phosphoric acid solution resulted in all specimens debonding with an ARI score of 0, although the mean shear bond strength was 8.11 MPa.

For Transcend brackets, only the 2% phosphoric acid solution produced ARI scores of 0 or 1 (Table 4). The other conditioners had a predominance (81.4%) of ARI scores of 2 or 3, with mean shear bond strengths that ranged from 9.42 to 12.00 MPa at a score of 2, and 8.89 to 13.26 MPa at a score of 3. The highest mean shear bond strengths were also recorded within the ARI parameters of 2 and 3.

For Spirit brackets, 91.4% of the brackets debonded with an ARI score of 3, indicating that all the adhesive remained on the enamel surface (Table 5). The mean shear bond strength under this ARI parameter ranged from 6.45 to 8.32 MPa. Overall, these mean shear bond strengths are considerably lower than those recorded for metal and Transcend brackets.

SEM observations

To enable a comparison with debonded samples, the bases of each bracket type were subjected to SEM examination (Figure 4A-C). Where a bracket debonded with an ARI score of 0, the adhesive adhered to the bracket base. The outline of the original attachment to the enamel surface can be clearly seen in the photomicrographs of debonded metal brackets (Figure 5A-B). An ARI score of 1 or 2 indicates that varying amounts of resin are left adhering to both the bracket and the tooth. An example of this is illustrated by the base of a Transcend bracket and the enamel surface to which it had been bonded (Figure 6A-B). Spirit brackets predominantly debonded by leaving all the resin on the enamel surface, and this can be seen clearly in the photomicrograph (Figure 7A-B).

Table 3
Clustering of mean shear bond strengths (MPa) according to each ARI[38] score and etchant type for metal brackets

ARI	Etchant	n	Mean ± SD
0	37 Pg	2	10.47 ± 1.14
	37 Ps	5	13.22 ± 1.19
	10 Mg	10	13.21 ± 1.96
	10 Ms *	9	13.73 ± 2.74
	10 Pg	8	13.30 ± 1.63
	10 Ps	7	13.59 ± 2.94
	2 Ps	10	8.11 ± 2.51
1	37 Pg	4	12.10 ± 2.04
	37 Ps *	2	16.77 ± 2.16
	10 Ms	1	15.05 N/A
	10 Pg	1	12.07 N/A
	10 Ps	1	13.14 N/A
2	37 Pg	1	6.73 N/A
	37 Ps	3	13.46 ± 2.31
	10 Ps	1	13.17 N/A
3	37 Pg	3	10.89 ± 2.35
	10 Pg	1	9.81 N/A
	10 Ps	1	9.66 N/A

*one sample in this group experienced enamel fracture upon debonding

In two instances, enamel fractures were recorded when debonding metal brackets when either 37% phosphoric or 10% maleic acid solutions had been the conditioning agents (Figure 8A-B). This can clearly be seen in the photomicrograph, where enamel can be seen on the bracket base with the accompanying defect on the tooth surface.

Discussion

Damage to enamel during the debonding of brackets has been, and still is, a concern to the clinician. It has been reported to occur both in vitro[14] and in vivo.[40] Several malpractice cases arising from enamel damage that occurred during debonding have been reported in the United States.[41] Since superior bond strengths have been reported in in vitro experiments,[13,15] there is a concern that these bond strengths are too high.[42] The use of acid conditioning agents of varying dilutions to reduce bond strengths has been suggested as a method of controlling damage to the enamel during debonding.[26] Since ceramic brackets appear to be a viable alternative to traditional metal brackets and the reportedly inferior plastic bracket,[43] the present study was designed to examine some of these factors.

It was shown in this study that, in general, there were no statistically significant differences ($p>0.05$) between maleic acid and phosphoric acid of comparable dilutions or between their respective aqueous and

Table 4
Clustering of mean shear bond strengths (MPa) according to each ARI[38] score and etchant type for Transcend brackets

ARI	Etchant	n	Mean ± SD
0	2 Ps	6	8.08 ± 0.68
1	10 Ms	1	9.99 N/A
	10 Ps	2	9.83 ± 3.07
	2 Ps	4	8.30 ± 1.01
2	37 Pg	5	11.20 ± 2.36
	37 Ps	7	10.79 ± 1.01
	10 Mg	4	10.68 ± 1.81
	10 Ms	6	9.42 ± 1.74
	10 Pg	9	12.00 ± 1.54
	10 Ps	5	9.61 ± 1.03
3	37 Pg	5	10.14 ± 1.49
	37 Ps	3	9.37 ± 0.09
	10 Mg	6	9.82 ± 1.37
	10 Ms	3	9.40 ± 0.56
	10 Pg	1	13.26 N/A
	10 Ps	3	8.89 ± 1.24

Table 5
Clustering of mean shear bond strengths (MPa) according to each ARI[38] score and etchant type for Spirit brackets

ARI	Etchant	n	Mean ± SD
0	10 Ps	1	6.30 N/A
	2 Ps	2	5.21 ± 1.30
1	37 Pg	1	5.68 N/A
	10 Mg	1	5.56 N/A
2	10 Ps	1	5.37 N/A
3	37 Pg	9	7.01 ± 1.54
	37 Ps	10	6.45 ± 0.56
	10 Mg	9	8.32 ± 0.61
	10 Ms	10	6.97 ± 1.05
	10 Pg	10	7.81 ± 0.62
	10 Ps	8	6.65 ± 0.42
	2 Ps	8	6.88 ± 0.91

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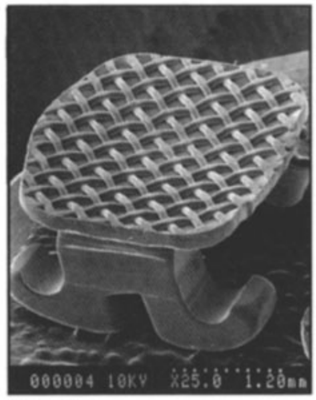

Figure 4A

SEM showing the base conformation of an unbonded metal bracket (x 25)

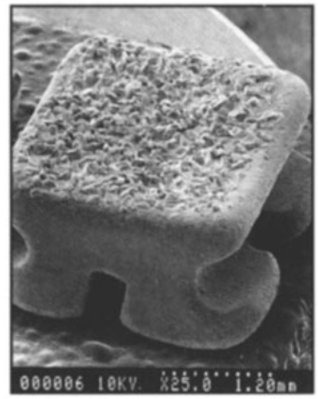

Figure 4B

SEM showing the base conformation of an unbonded Transcend bracket (x 25)

Figure 4C

SEM showing the base conformation of an unbonded Spirit bracket (x 25)

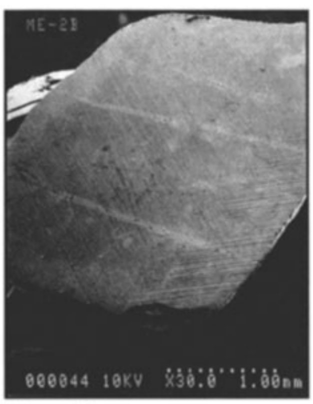

Figure 5A

SEM showing the base of a debonded metal bracket. Note that the majority of the resin is removed with the bracket (x 30)

Figure 5B

SEM showing the enamel surface following debonding. Note that the enamel surface is devoid of resin, ARI score = 0 (x 30)

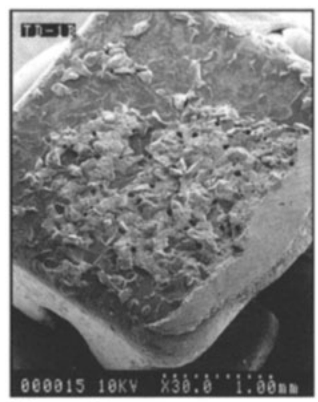

Figure 6A

SEM showing the base of a debonded Transcend bracket. Note that less than half the resin is left adhering to the bracket base (x 30)

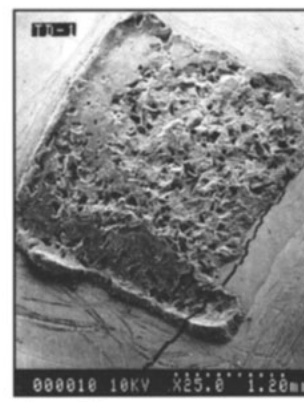

Figure 6B

SEM showing the enamel surface following debonding . More than half the resin is left adhering to the enamel surface, ARI score = 2 (x 30)

Figure 7A

SEM showing the base of a debonded Spirit bracket. Note that no resin is left adhering to the bracket base (x 30)

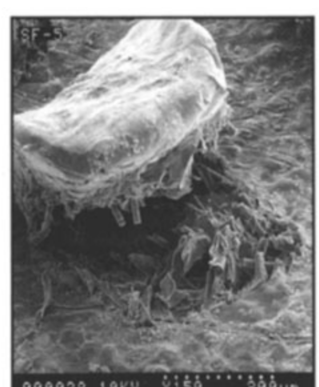

Figure 7B

SEM of a fractured mush-room-shaped projection, representative of the Spirit bracket group, a possible explanation for the low shear bond strengths and ARI score = 3 (x150)

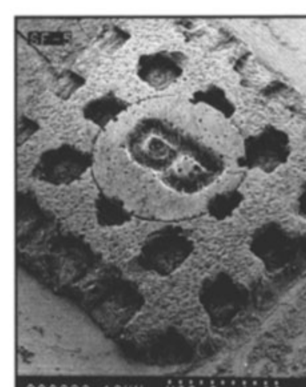

Figure 7C

SEM showing the enamel surface following debonding. Note that all the resin is left adhering to the enamel surface, ARI score = 3 (x 30)

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gel preparations for each bracket type. The ARI scores similarly showed that minimal differences existed between phosphoric and maleic acid conditioners for each bracket type. In the case of metal brackets, most ARI scores were 0 or 1. For the ceramic Transcend brackets, the majority of the scores were 2 or 3, indicating that a preponderance of resin was left on the enamel surface; the exception was with the 2% phosphoric acid solution with ceramic brackets, where most ARI scores were 0 or 1. In contrast, the polycarbonate Spirit brackets showed ARI scores that were predominately 3, indicating that all the resin was left on the enamel surface. These results clearly have implications in the clean-up procedures that follow debonding and possible damage to the enamel surface.

The factors that primarily affect ARI scores are probably the acidic conditioners and the design and rigidity of the bracket base. Phosphoric and maleic acids etch and condition the enamel surface in a similar manner, although 10% maleic acid has been shown to remove significantly less enamel than 35% phosphoric acid gel.[44] SEM examination of acid-conditioned surfaces has shown that, with minor exceptions, the morphological appearance of surfaces conditioned with phosphoric and maleic acids is similar.[8,44,45] The reaction products of these acids, however, differ somewhat. The reaction product of maleic acid is calcium maleate, which is soluble and as a result, is probably more thoroughly removed when the tooth surfaced is washed prior to drying and application of the adhesive.[46] For phosphoric acid conditioners whose concentrations exceed 27%, the principal reaction product is monocalcium phosphate monohydrate, another relatively soluble compound that would be effectively washed away.[46,47] On the other hand, the reaction product of phosphoric

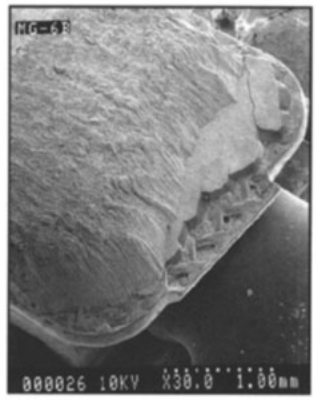

Figure 8A

SEM showing resin and enamel adhering to the base of a metal bracket following debonding (x 30)

Figure 8B

SEM showing the enamel surface following debonding of the metal bracket. Note defect in the enamel surface that occurred as a result of enamel fracture (x 30)

acid in concentrations of less than 27% is the less soluble dicalcium phosphate dihydrate, and this could have an adverse effect on the strength of the bond.

Phosphoric acid conditioners in concentrations of 2% have been shown to result in minimal loss of superficial enamel with a concomitant reduction in the length of the resin tags that penetrate the enamel.[25,45] It has also been shown that 40% phosphoric acid produces a mean shear bond strength similar to that produced by a 2% phosphoric acid conditioner.[48] The results obtained in this study indicate that for metal brackets, the mean shear bond strength produced by a 37% commercial phosphoric acid gel is statistically comparable to that produced by a 2% solution. The bond strength produced by the latter, however, is statistically significantly different from those produced by all the other phosphoric solutions and gels. For Transcend brackets, a 2% phosphoric acid solution produces mean shear bond strengths that are statistically comparable with those produced by a 10% phosphoric acid solution and both 10% maleic acid solutions and gels, but these bond strengths are statistically significantly different from those produced by 10% phosphoric acid gel and 37% phosphoric acid solution and gel. In the case of Spirit brackets, with the exception of 10% maleic acid gel, a 2% solution of phosphoric acid produces mean shear bond strengths that are comparable with those produced by all other concentrations of phosphoric and maleic acid solutions and gels. It has been suggested that a clinically adequate bond strength for an orthodontic bracket is in the range of 6 to 8 MPa, and the mean shear bond strengths reported in the present study are well within or exceed these limits.[4,49] From the results reported here, it would appear that phosphoric acid gels and solutions in concentrations ranging from 2% to 37% and 10% maleic acid gel and solution produce bonds that are strong enough to withstand most clinical forces despite the variations in their etching patterns and the solubility of their various reaction products.

The incidence of enamel fracture during debonding older generation ceramic brackets has been reported to be as high as 40%.[11,12,14,15] These findings were the result of in vitro investigations in which the mean shear bond strengths ranged from 18.8 to 28.3 MPa, and these bond strengths are considerably higher than those reported in the present study. However, mean shear bond

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strengths similar to those found in the present study have been reported.[5] These latter studies used the current generation of Transcend ceramic bracket (Transcend 6000®). In all probability, these lower shear bond strengths are due to the change in base design because the latest Transcend brackets rely on irregularities in the bracket base for micromechanical retention, whereas the former bracket relied on chemical retention or a textured base for mechanical retention.[15] Ideally, to avoid enamel fracture, the adhesive failure should occur between the bracket base and the adhesive rather than between the adhesive and the enamel.[50, 51] In the present study, the majority of bond failures for Transcend and Spirit brackets exhibited this mode of failure. Interestingly, only two instances of enamel fracture were recorded and these were associated with metal brackets, not ceramic ones. In each case the mean shear bond strength was greater than 15 MPa. Although enamel fractures during the debonding of metal brackets are uncommon, they have been reported, particularly where conditioners are of higher concentration and extended conditioning times are used.[10,27, 32] As a result, it may be concluded that enamel fracture is more likely to occur with adhesive/bracket/conditioner combinations that produce high shear bond strengths.

The ARI index provides information that has considerable clinical implications for clean-up following debonding of brackets. Minimizing the amount of residual resin left adhering to the enamel surface minimizes iatrogenic damage to the enamel during clean-up procedures. An ARI score of 0 indicates that all of the resin is removed during debonding. It would appear that any bracket/resin/conditioner combination that produces this result is ideal, since removal of resin following debonding is not only time-consuming, but can be damaging as well.[52]

An attempt was made to determine if an ideal conditioner could be identified for each bracket type. The search was centered around those conditioners that produced the lowest ARI scores, since these scores indicate that a minimal amount of adhesive is left on the enamel surface following debonding. A low ARI score implies that there is a minimal risk of iatrogenic damage to the enamel surface when residual resin composite is removed following debonding and clean-up procedures.[52] In addition, to fulfill these criteria, clinically adequate bond strength should be maintained and the risk of enamel fracture should be minimal.

Acid conditioning of the enamel surface has been shown to produce microporosities up to 50 mm in depth, and it has also been estimated that the clean-up procedure may remove up to 55.6 mm of surface enamel.[53] Thus, the clean-up procedure can result in removal of enamel in excess of the original depth of etch. Carstensen[26] has shown that clean-up was more difficult following debonding when enamel was conditioned with 37% phosphoric acid compared with a 2% conditioner. The resin remnants associated with the former conditioner necessitated removal with air-cooled tungsten carbide burs, whereas those left from the latter conditioner were easily scraped off with a scaler. These results would suggest that if clinically acceptable bond strengths can be attained with dilute acids, the clean-up procedures would be less damaging since the adhesive resin does not penetrate a lightly conditioned surface to any great depth.[45] Even if the majority of the resin remains on the enamel following the debonding procedure, it is clearly easier to remove and at the same time the integrity of the surface enamel is preserved.

The results of this study suggest that clinically acceptable bond strengths may be obtained for stainless steel, ceramic, and polycarbonate brackets using phosphoric acid conditioners that are more dilute than those commercially available. Maleic acid gels and solutions, which did not show the same chalky white appearance following etching, produced comparable results. Even though the ARI scores for the ceramic and polycarbonate brackets indicate that the majority of the bonding resin is left adhering to the tooth following debonding, the evidence from this and other investigations suggest that clean-up procedures may be less damaging to the enamel and easier for the clinician to perform.

Conclusions

1. Clinicians should pursue the goals of matching the conditioner to the bracket and to the tooth being bonded.
2. Particularly important is the maxillary anterior region where esthetics (enamel fracture and discoloration) is a major consideration.
3. Total removal of resin during the initial debonding procedure should be the goal, taking care to minimize iatrogenic damage to enamel.
4. The latter reduces the risk of staining the adherent residual resin in the long-term.

Acknowledgments

The authors wish to acknowledge the invaluable assistance of Mr. Robert Chernecky and Dr. Kiran Kulkarni.

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