

Factors Affecting the Shear Bond Strength of Orthodontic Brackets to Porcelain

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Abstract: *The aim of this investigation was to establish a regime for orthodontic bonding to feldspathic porcelain, which ensures adequate bond strength (6–8 MPa) with minimal damage on debond and consisted of an ex vivo investigation measuring the effects of porcelain surface preparation and thermocycling on shear bond strength of orthodontic brackets.*

One-hundred-and-twenty feldspathic porcelain bonded crown surfaces were divided into 12 equally-sized groups to assess the effects of: (1) glaze removal, (2) application of hydrofluoric acid, phosphoric acid, or omission of acid treatment, and (3) silane priming upon the bond strength of premolar brackets bonded with Right-on™ composite resin adhesive. Specimens were subjected to thermocycling and then to shear debonding forces on an Instron machine.

Removal of the porcelain glaze, or use of hydrofluoric acid, prior to bonding were found to be unnecessary to secure the target bond strength. Hydrofluoric acid application was associated with increased porcelain surface damage. Thermocycling caused a significant reduction in shear bond strength to porcelain ($P < 0.001$). The best regime for orthodontic bonding to feldspathic porcelain was to apply phosphoric acid for 60 seconds, and prime with silane prior to bonding. Usually the porcelain surfaces could be repolished.

Index words: Etching, Porcelain Bonding, Surface Preparation, Porcelain Fracture.

Refereed Paper

Introduction

Dental porcelain is a popular restorative material, especially for adult patients, where it is used for restorations such as veneers, crowns, and bridges. Increased demand by adults for orthodontic treatment (Nattrass and Sandy, 1995) may mean that orthodontists will more often find it necessary to apply orthodontic attachments to teeth featuring a porcelain restoration. The task of successfully and reversibly attaching an orthodontic bracket to a porcelain surface for the duration of a course of fixed appliance treatment may be frustrated by bond failure or porcelain surface damage upon debond.

- A bracket may be applied to a porcelain-restored tooth indirectly by means of steel bands (Smith *et al.*, 1988).

Alternatively, they could be applied directly by bonding to:

- porcelain roughened with diamond burs (Pratt *et al.*, 1989; Özden *et al.*, 1994), green stones (Eustaquio *et al.*, 1988; Kao *et al.*, 1988), or abrasive disks (Hulström and Bergman, 1993);
- porcelain roughened by acid etching or sand blasting (Wolf *et al.*, 1993);
- a retention cavity cut in the porcelain surface (Wood *et al.*, 1986);
- porcelain primed with silane for chemical retention (Major *et al.*, 1995; Nebbe and Stein, 1996).
- porcelain primed by 'new generation' bonding agents such as 4-META resins (Zachrisson *et al.*, 1996).

Each method has disadvantages: bands have poor appearance and placement may be difficult (Nattrass and Sandy, 1995), while plaque control problems may arise around banded teeth (Boyd and Baumrind, 1992); roughening or cutting damages the porcelain surface (Messer *et al.*, 1991), and toxic agents, such as hydrofluoric acid, pose dangers to patients and staff (Hayakawa *et al.*, 1992).

Objectives

The aim of the present study was to examine the effect of several variables on the bond strength of mesh-backed orthodontic brackets to porcelain bonded to metal crowns manufactured using one brand of feldspathic porcelain (Ivoclar® Vita-matched, IPS Liechtenstein) and to examine the effects of thermocycling on shear bond strength. The variables examined were:

- glaze preservation or removal;
- surface treatment with acid or omission of acid treatment;
- surface treatment with silane or omission of silane treatment.

Materials and Methods

One-hundred-and-thirty upper first premolar brackets (A Company Straight Wire® 'A' Company, 11436 Sorrento Valley Road, San Diego, U.S.A.) were divided into 13 equal groups. Sixty-five feldspathic porcelain bonded to metal (Panabond NP®, Panadent Ltd, London, U.K.)

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TABLE 1 Description of experimental groups and variables

The experimental groups were designed as follows ($n = 10$ in each group):					
(1) G	(2) G + P	(3) G + HF	(4) G + Si	(5) G + P + Si	(6) G + HF + Si
(7) D	(8) D + P	(9) D + HF	(10) D + Si	(11) D + P + Si	(12) D + HF + Si
The groups used to investigate thermocycling were:					
D + HF + Si(Tc), D + HF + Si(not Tc),					
G glaze left intact					
D glaze removed by a hand held aluminium oxide sandblasting unit					
P surface application of 37 per cent phosphoric acid for 60 seconds					
HF surface application of 9.6 per cent hydrofluoric acid for 3 minutes					
Si application of three coats of Scotchprime silane, followed by Scotchbond adhesive, light-cured for 20 seconds					
Tc water-stored at 37°C for 24 hours followed by thermocycling for 500 cycles between 5 and 55°C					

crowns were fabricated in the shape of an upper first pre-molar tooth, but with two similarly sized and shaped 'buccal' cusps, thereby allowing two brackets to be bonded to each crown. The crowns were all made by one skilled ceramic technician.

The porcelain glaze was preserved in half of the crowns, while glaze was removed with a hand-held sandblaster in the remainder. The total number of crowns was then divided into three equal groups, with an equal distribution of glazed and de-glazed surfaces: one-third of the crowns did not receive acid treatment, the second group was surface treated with 37 per cent phosphoric acid (supplied with Right on®) for 60 seconds, and the final one third, was etched with 9.6 per cent hydrofluoric acid (Ultradent® porcelain etch, Ultradent, Utah, U.S.A.) for 3 minutes. Finally, the total number of crowns was divided into two equal groups, once again ensuring equal distribution of the variables. Half of the crowns were primed with Scotchprime® silane coupling agent and Scotchbond® dental adhesive prior to bonding, while the rest were not silane-coated. The dispersal of variables produced 12 groups, each with 10 specimens (Table 1). A final group was produced by treating a further 10 porcelain surfaces similarly to the D-HF-Si group, these specimens were not thermocycled. All brackets were applied using Right-on® composite resin adhesive with firm pressure and immediate removal of excess material using a periodontal scaler.

Specimens were stored in water at 37°C for 24 hours, and subsequently thermocycled between 5 and 55°C for 500 cycles as recommended by the International Organization for Standardization (ISO TR 11405, 1994). Specimens were then subjected to shear forces by attaching a steel wire loop under the occlusal tie wings of the bracket in an Instron testing machine as described by Fox *et al.* (1994), with a cross-head speed of 5 mm per minute at a full scale load of 200 N, until bond failure occurred. Following bond failure, the crowns were examined under light stereomicroscopy at $\times 20$ magnification to establish the amount of composite resin left behind, according to the Adhesive Remnant Index (Årtun and Bergland, 1984).

All composite remnants were then removed using scaling instruments after bulk reduction with a twelve-fluted tungsten carbide bur in a slow-speed handpiece. The porcelain surfaces were subsequently re-examined with $\times 20$ stereomicroscopy to assess damage which may have occurred to the porcelain, using the Porcelain Fracture Index developed for this study. Finally, the porcelain surfaces were polished with Chameleon diamond polishing

paste and wheels in an attempt to establish a glaze-like surface.

Statistical Analysis

Statistical analysis was performed using Minitab, Release 10.2 and S.P.S.S. (Statistical package for Social Sciences for Windows, Release 7.5). Multiple Analysis of Variance with replicates, Tukey pairwise analysis and Student's *t*-test were employed for quantitative data, while log linear analysis was applied to the qualitative data of the Porcelain Fracture and the Adhesive Remnant Indices.

Results

Table 2 shows results of shear bond strength tests for the 12 possible porcelain bonding regimes. Silane priming had the greatest single influence upon bond strength. The mean shear strength for the six groups in which silane was used was 9.14 MPa, against 3.56 MPa when silane priming was omitted. Glaze removal increased bond strength from 5.38 to 6.14 MPa across the range of specimens, whilst the use of acid resulted in an increase from 4.49 to 6.39 MPa. Thermocycling weakened bond strength from a mean of 18.69–9.53 MPa.

Data for the Adhesive Remnant Index (Årtun and Bergland, 1984) and the Porcelain Fracture Index are shown in Tables 3 and 4, respectively. No pattern was evident to associate specific variables with post-debond

TABLE 2 Shear bond strength values for porcelain and enamel specimens

Specimen type	Mean shear bond strength (MPa)	Standard deviation (MPa)
G	0	0
G-P	0	0
G-HF	3.52	0.24
D	1.47	0.47
D-P	3.07	0.57
D-HF	6.16	1.42
G-Si	8.42	2.59
G-P-Si	10.04	2.84
G-HF-Si	10.29	1.3
D-Si	8.06	1.84
D-P-Si	8.52	1.03
D-HF-Si	9.53	1.48
D-HF-Si (not thermocycled)	18.69	1.4

TABLE 3 Adhesive Remnant Index scores (numbers of specimens in each group per ARI score)

Variables			Adhesive	Remnant	Index	Score
Glaze	Silane	Acid	0	1	2	3
Glazed	Yes	Phosphoric	5	0	4	1
		Hydrofluoric	0	4	5	1
		None	0	3	5	2
	No	Phosphoric	10	0	0	0
		Hydrofluoric	7	3	0	0
		None	10	0	0	0
Deglazed	Yes	Phosphoric	0	3	5	2
		Hydrofluoric	0	4	5	1
		None	0	5	2	3
	No	Phosphoric	6	4	0	0
		Hydrofluoric	0	3	7	0
		None	8	2	0	0

Adhesive Remnant Index (Årtun and Bergland, 1984): 0, all adhesive removed with bracket; 1, adhesive remnants covering less than 50 per cent of former bracket site; 2, adhesive remnants covering more than 50 per cent of former bracket site; 3, all adhesive left behind on tooth surface with clear imprint of bracket base.

TABLE 4 Porcelain Fracture Index scores (numbers of specimens in each group per PFI score)

Variables			Porcelain	Fracture	Index	Scores
Glaze	Silane	Acid	0	1	2	3
Glazed	Yes	Phosphoric	8	1	0	1
		Hydrofluoric	0	2	1	7
		None	5	1	2	2
	No	Phosphoric	10	0	0	0
		Hydrofluoric	10	0	0	5
		None	10	0	0	0
Deglazed	Yes	Phosphoric	5	2	0	3
		Hydrofluoric	0	1	4	5
		None	5	1	0	4
	No	Phosphoric	10	0	0	0
		Hydrofluoric	10	0	0	0
		None	10	0	0	0

Porcelain Fracture Index: 0, surface intact or in same condition as before bonding procedure; 1, surface damage limited to glaze layer or very superficial porcelain; 2, surface damage which features significant loss of porcelain requiring restoration of the defect by composite resin or replacement of the restoration; 3, surface damage where the core metal has been exposed due to the depth of the cohesive failure.

Adhesive Remnant Index scores. The Porcelain Fracture Index did, however, demonstrate strong associations between the extent of porcelain damage after debond and the bonding regime.

ANOVA indicated significant differences between variables affecting bond strength as follows:

- presence or absence of an intact porcelain glaze ($P < 0.01$);
- application or omission of acid to the porcelain surface prior to bonding ($P < 0.001$);
- use or omission of silane ($P < 0.001$).

ANOVA was also used to examine paired inter-group interactions, that is to say: glaze/acid, glaze/silane, and silane/acid interactions. The only variable which had a consistent and strong effect upon bond strength was the use or omission of silane.

ANOVA followed by a Tukey analysis indicated significant differences between those groups in which hydrofluoric acid was employed, and those groups without either hydrofluoric or phosphoric acid. No difference was detected between the hydrofluoric and phosphoric acid groups, or between the phosphoric acid and non acid-treated specimens ($P > 0.05$).

Student's *t*-test suggested that there were significant differences between thermocycled and non-thermocycled specimens from the deglazed-hydrofluoricacid-silane group ($P < 0.001$).

The large number of 'zero' scores prevented full analysis for all four porcelain fracture index scores. Results were therefore combined into two groups based upon their clinical relevance: PFI scores of 0 and 1, which could be restored by polishing and PFI scores of 2 and 3, which indicated the need for repair or replacement of the porcelain. This model showed that hydrofluoric acid treatment produced more damage than phosphoric acid application ($z > 1.96$, equivalent to a confidence limit of 95 per cent).

Examination of polished porcelain surfaces using light microscopy and scanning electron microscopy indicated that polishing with a diamond polishing paste could restore a surface smoothness that surpassed that of the original porcelain glaze.

Discussion

The maximum bond strength which may be achieved to porcelain is not usually required for orthodontic purposes. The ideal bond should be sufficiently strong to endure a course of orthodontic treatment, yet be sufficiently weak to permit restoration of the porcelain surface following bracket removal.

There are few scientifically-based recommendations in the literature for a minimum orthodontic bracket shear bond strength. Reynolds (1975) recommended a tensile force of 60 kg/cm² to 80 kg/cm², while Newman (1965) stated that 14 kg/cm² was the maximum that should be applied by an orthodontic appliance. Whitlock *et al.* (1994), based upon the work of Reynolds, also suggested that 6–8 MPa was adequate for orthodontic attachments and this was used in the present study, along with the Adhesive Remnant Index and the Porcelain Fracture Index to establish which bond regime produced adequate strength in terms of bracket attachment, with least porcelain surface damage following bracket removal.

The decision to use 10 specimens per group was made partly due the high cost of the porcelain crowns, but is well justified by the acceptable standard deviations in shear bond strengths and by the high significance values for inter-group statistical tests. A higher number of specimens per group has been recommended for tests involving enamel surfaces (Fox *et al.*, 1994), where it is possible that greater specimen variation would occur than that seen with porcelain crowns made to one die by a skilled ceramist.

Specimens were subjected to thermocycling as a means of artificially ageing or weakening bonds prior to testing, as described by the Organization for International Standardization (ISO TR 11405, 1994, Kao *et al.*, 1988; Zachrisson *et al.*, 1996; Sorenson *et al.*, 1991). The effect of thermocycling was marked: the mean bond strength being

18.69 MPa for non-thermocycled D-HF-Si porcelain compared to 9.53 MPa for thermocycled specimens. The shear bond strengths achieved in this study after thermocycling, compare somewhat modestly with those in similar studies, many of which employed thermocycling (Table 5).

Glaze removal has been advocated in order to create mechanical retention for the adhesive agent (Hulterström and Bergman, 1993). Unfortunately, glaze removal by a diamond bur or green stone may damage porcelain by scoring the surface and an additional disadvantage of glaze removal is a reduction of 50 per cent in transverse strength (Phillips, 1991). Sandblasting with microscopic particles of aluminium oxide to remove glaze may be better than using burs or stones since only a small amount of surface is removed and the procedure is more uniform (Zachrisson *et al.*, 1996). In view of the many difficulties associated with glaze removal, it is reassuring to note that satisfactory bond strengths have been achieved to glazed porcelain (Eustaquio *et al.*, 1988; Kao *et al.*, 1988). Data from the present study suggest that glaze removal prior to bonding does not confer advantage over alternative and less damaging bonding regimes. The use of strong acids to etch porcelain as suggested by Calamia (1983) may produce strong bond strengths, since the action of an acid such as 9.6 per cent hydrofluoric is to create a series of surface pits by preferential dissolution of the glass phase from the ceramic matrix (Al Edris *et al.*, 1990). However, hydrofluoric acid must be used with great care, as it is extremely corrosive, and is capable of causing severe trauma to soft tissues and tooth substance (Hayakawa *et al.*, 1992). Phosphoric acid, at 37 per cent concentration, does not etch porcelain and, consequently, unlike hydrofluoric acid, it does not produce physical or topographical changes in the porcelain surface. Instead, the effect of phosphoric acid is to neutralize the alkalinity of the adsorbed water layer, which is present on all ceramic restorations in the mouth and, thereby, enhance the chemical activity of any silane primer subsequently applied (Wolf *et al.*, 1993). ANOVA showed statistically significant differences between the groups etched with 9.6 per cent hydrofluoric acid and unetched specimens ($P < 0.01$), but neither of these

variables differed significantly from the 37 per cent phosphoric acid treated groups.

In order to clarify the benefits or otherwise of the two forms of acid treatment, it is necessary to consider the ARI (Adhesive Remnant Index) and PFI (Porcelain Fracture Index) results. Log linear analysis established that there was no relationship between bonding regime and the Adhesive Remnant Index score following bracket removal.

PFI scores for post-debond specimens indicated that all specimens which had not been silane-treated were left completely intact, so that they all scored zero on the PFI. However, silane application was a prerequisite for satisfactory bond strength, as the omission of silane was associated with significant reductions in bond strength. Use of hydrofluoric acid was associated with high PFI scores, while the use of phosphoric acid was associated with low PFI scores.

Therefore, since a low PFI score is preferable to a high score, phosphoric acid treatment of the porcelain surface is preferable to the omission of acid treatment, which in turn is to be preferred to etching with hydrofluoric acid.

Silane bonding acts as a chemical link between the inorganic ceramic surface and the organic resin adhesive agent (Pleuddeman, 1982). Superior bond strengths to porcelain have been reported following the use of a silane coupling agent (Lacy *et al.*, 1988; Kao and Johnston, 1991; Whitlock *et al.*, 1994). Porcelain etching without using a silane primer has also been found to be no better than simply roughening the porcelain mechanically before composite application (Wood *et al.*, 1986; Lacy *et al.*, 1988). Application of silane to porcelain before bonding may produce such high bond strengths that there is a tendency for cohesive failure of porcelain upon debond, especially when the porcelain has been acid-etched (Newburg and Pameijer, 1978; Lacy *et al.*, 1988; Lu *et al.*, 1992).

Data from the present investigation strongly advocate the use of a porcelain primer before bracket application with a composite resin. The best balance between bond strength and avoidance of severe porcelain surface fractures upon debond was achieved by preserving the glaze, treating the porcelain surface with 37 per cent phosphoric acid for sixty seconds, applying three coats of Scotchprime®

TABLE 5 Examples of bond strengths to porcelain from other studies

Authors	Bond regime	Thermocycled	Mean bond strength (MPa)	Standard deviation (MPa)
Zachrisson <i>et al.</i> (1996)	D + HF	Yes	(Tensile) 11.5	2.8
	D + S	Yes	(Tensile) 11.6	2.9
	D	Yes	(Tensile) 2.8	0.7
Nebbe <i>et al.</i> (1996)	D + P + S	No	(Shear) 15.61	3.99
	G + P + S	No	(Shear) 19.78	4.66
Major <i>et al.</i> (1995)	HF + S	No	(Shear) 13.53	3.34
Wolf <i>et al.</i> (1993)	G + HF + S	No	(Tensile) 27	Not reported
	D + S	No	(Tensile) 19	Not reported
	D + S	No	(Shear) 16.86	4.7
Kao and Johnston (1991)	G + S	Yes	(Shear) 13.78	1.78
	D + S	Yes	(Shear) 18.89	2.67
Kao <i>et al.</i> (1988)	D + S	No	(Shear) 20.31	Not reported
	G + S	No	(Shear) 13.84	Not reported
	D	No	(Shear) 12.59	Not reported
	G	No	(Shear) 9.74	Not reported
Smith <i>et al.</i> (1988)	D + S	Yes	(Shear) 8.33	2.22
	D	Yes	(Shear) 2.78	1.39
	G + S	Yes	(Shear) 10.56	3.89

silane and, finally, applying the light-cured Scotchbond® unfilled resin from the same kit, before seating the bracket with Right-on® composite resin.

Summary and Conclusions

- Within the limitations of an *ex vivo* study, a regime for orthodontic bonding to one particular brand of feldspathic porcelain has been identified, which combines satisfactory bond strengths with an acceptable incidence of porcelain damage following bracket removal.
- The application of 37 per cent phosphoric acid to glazed feldspathic porcelain for 60 seconds, followed by Scotchprime® silane priming agent and Scotchbond 2® light-cure dental adhesive, prior to bracket placement with Right-on® composite resin resulted in satisfactory bond strengths for orthodontic purposes.
- It was not necessary to use hydrofluoric acid, which is highly toxic and corrosive, to achieve satisfactory bond strengths.
- The use of silane prior to bonding was the single most important factor in determining satisfactory bond strength.
- According to the Adhesive Remnant Index scores, the amount of composite resin remaining on the porcelain surfaces was independent of the bonding regime employed.
- The Porcelain Fracture Index scores indicated that etching with hydrofluoric acid, especially in association with silane priming, was associated with a higher incidence of severe porcelain damage. Lower PFI scores were noted for those specimens which did not receive acid treatment, but the lowest PFI scores were associated with the use of phosphoric acid.
- Porcelain surfaces with PFI scores of 0 or 1 were readily polished to an acceptable glaze-like appearance, and this was verified by light microscope examination and scanning electron microscopy.

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Details of manufacturers:

A Company, 11436 Sorrento Valley Road, San Diego, California

3M Unitek, 2724 South Peck Road, Monrovia, California

TP Orthodontics, 100 Center Plaza, La Porte, Indiana

Ivoclar® Vita-matched (IPS Liechtenstein)

Panabond NP®, Panadent Ltd. London, UK

Keramo 3®, Renfert GmbH, Hilzingen, Germany

Ultradent® porcelain etch, Utah, USA