European Journal of Orthodontics 34 (2012) 505–511
doi:10.1093/ejo/cjr043
Advance Access Publication 29 March 2011

In vitro orthodontic bracket bonding to porcelain

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SUMMARY This *in vitro* study investigated the influence of using different combinations of bracket, adhesive, and light-curing source on the tensile bond strength to porcelain and on failure patterns at debonding. Tensile tests were performed using: one ceramic bracket versus one metal bracket, two orthodontic composites; type bisphenol A-glycidyldimethacrylate and urethane dimethacrylate (UDMA), and four light-curing units with the same range of emission spectrum but various light intensities: three light-emitting diode (LED) units and one halogen-based unit. One hundred and sixty porcelain samples were randomly divided into 16 equal groups. The porcelain surface was conditioned with 9 per cent hydrofluoric acid before silane application. The composite was photo-polymerized for 40 seconds. After storage in water at 37°C for 24 hours, the samples were subjected to tensile force until bond failure. Bond strength and bond failure mode were recorded; results were analysed ($\alpha = 0.05$) using R language; linear model with constant variance for the bond strength and multinomial distribution for the failure mode. The bond strength in all groups was sufficient to withstand orthodontic treatment (>6 MPa). There was no statistical difference between the adhesives, but comparing bracket × light interaction, it was significantly higher with the ceramic bracket. No significant differences were seen between the metal bracket groups, but for the ceramic bracket, the results were significantly higher with the LED light. No fracture was observed in porcelain with the metal bracket but it occurred in 35 per cent of the ceramic bracket samples and the risk was higher when using UDMA composite and lower with LED high intensity light.

Introduction

The past decade has witnessed rapid advancement in various materials science fields and in dental specialities. This advancement in orthodontic materials has led to growth in product varieties; bonding systems, light-curing sources, brackets, and treatment concepts. In agreement with Eliades (2006), this rapid advancement has changed 'the commercial life of materials; it is common for materials, introduced just a few years ago, to become no longer in use, a possible derivative of the lack of quality control, and research and design deficiencies. Therefore, the clinician faces a handicap in the race with technology and the requirement to obtain familiarity with new materials and techniques, some of which might not have advantages over their predecessors'.

In addition, it is known that the advancements in orthodontic materials and treatment techniques have not only affected the orthodontic practice 'technically' but also resulted in changing the 'population of patients' by including and encouraging an increased number of adult patients to ask for orthodontic treatment.

As porcelain restorations are widely used to restore damaged or missing teeth in adults, the orthodontic treatment for such patients must take into consideration the difficulty in bonding brackets to porcelain, whose glazed surface is not amenable to resin penetration and on the other hand must consider a safe removal of brackets to reduce to a minimum any possible damage to the restoration surface.

Previous studies showed that bonding strength of brackets to porcelain restorations and the failure model depend on many variables; porcelain type and surface conditioning, bracket material and its base design and retention mode, composition and physical properties of the bonding adhesive, and the light-curing source. Thus, for clinically successful orthodontic treatment, the choice from the various materials and products in combinations may remain the decisive factor.

Nowadays, there is a wide range of various products used in orthodontics, such as the adhesives with different molecules of resin and many products for surface treatment before bonding.

Adhesive composites consist of a blend of synthetic resin and inorganic reinforcing fillers. All resins contain methacrylate or acrylate giving the molecular structures of the most commonly used monomers; bisphenol A-glycidyldimethacrylate (Bis-GMA) and urethane dimethacrylate (UDMA), together with the co-monomer [triethylene glycol dimethacrylate (TEGMA)]. While Bis-GMA has a high viscosity and requires dilution with a more fluid resin, UDMA-type monomers have relatively low viscosity and do not need the use of diluents (Faltermeier *et al.*, 2007). Inorganic fillers are added to the resin to increase strength and stiffness, to facilitate manipulation, and to reduce dimensional changes (Faltermeier *et al.*, 2007; Vilchis *et al.*, 2008). In light-cured adhesives, the filler volume fraction plays a role in the extent of polymerization by inducing refraction and scattering of light, thereby reducing its intensity in the bulk material (Eliades, 2006).

In light-cured adhesives, for a given monomer system, the extent of polymerization depends not only on exposure time and photoinitiator concentration but also on light intensity of the curing unit at the peak absorbance wavelength of the photoinitiator. The spectral distribution of the light source significantly affects polymerization of the material (Eliades, 2006; Gritsch *et al.*, 2008). The parameters of visible light that have an effect on adhesive properties are energy and power, diameter (of aperture), distance, and setting time (Swanson *et al.*, 2004; Usumez *et al.*, 2004; Gritsch *et al.*, 2008).

Because of its inert surface, porcelain does not adhere to other materials and needs surface treatment altering its characteristics to provide sufficient bond strength between porcelain surface and bracket to withstand the forces needed for orthodontic treatment (Cochran *et al.*, 1997; Abu Alhaija and Al-Wahadni, 2007). One of the frequently used chemical agents to produce micromechanical retention is hydrofluoric acid (HF). Etching with it produces, in non-aluminous porcelain, a uniform in-depth penetration providing micromechanical retention for bonding without changing the surface (Abu Alhaija and Al-Wahadni, 2007). Despite the inconvenience of its intraoral manipulation, etching with it followed by silane application was found to be an appropriate and efficient conditioning method (Zachrisson *et al.*, 1996; Schmage *et al.*, 2003; Abu Alhaija and Al-Wahadni, 2007). The use of silane, as a coupling agent after etching, increases the bond strength as it provides chemical retention by acting as an interface between the silica in porcelain and the organic groups of the bonding composite (Smith *et al.*, 1988; Zachrisson *et al.*, 1996; Schmage *et al.*, 2003; Abu Alhaija and Al-Wahadni, 2007).

The purpose of this study was to evaluate and compare the adhesion of ceramic and metal brackets to porcelain, treated with HF and silane, taking in consideration at the same time a combination of variables; bracket material, adhesive composite, and light-curing unit (LCU), which can influence tensile bond strength and failure models. The choice was to select products, equipments, and surface treatment from those frequently used clinically.

Materials and methods

A total of 160 glazed porcelain samples were produced. The samples were made from fluorapatite glass-ceramic (IPS d.SIGN; Ivoclar Vivadent, Schaan, Liechtenstein) with a template to obtain the same size and baked under vacuum at 870°C. To obtain horizontal porcelain surfaces and to standardize the prospective bonding surface, the porcelain samples were polished with abrasive discs (Escil, Chassieu, France). The glaze was baked at 830°C. Each porcelain sample was individually embedded in autopolymerizing acrylic resin (Mecaprex; KMV, Grenoble, France).

The samples were randomly divided into 16 groups of 10 according to the test to be undertaken, the type of bracket, composite, and the LCU used.

Brackets

Metal and ceramic brackets, from the same manufacturer, were used. Both were upper central incisor brackets (0.022 inch slot), as an aesthetic porcelain restoration is often on such teeth. Their type, composition, retention mode, and commercial names are shown in Table 1. The bracket base average surface area was calculated by measuring the base periphery of five brackets.

The metal bracket base surface area was estimated to be 13.0 mm^2. Retention of the base was mechanical ensured by a three-ply assembly and micro-etching.

The ceramic bracket base average surface area was estimated to be 11.88 mm^2. The base bracket was provided with patented dimpled chemo/mechanical retention. According to the manufacturer's description, the base layers contain a wider mesh over a tighter mesh for more surface areas without raising the profile. The base adds micro-etching for retention.

The mechanical retention system of the base, SuperMesh® ME Base (GAC International Inc., Bohemia, New York, USA), was the same for both the ceramic and metal brackets. The choice of brackets from the same manufacturer was for easier comparison as they have similar base design.

Table 1 The used brackets.

Type	Composition	Retention mode	Product	Manufacturer
Metal	Stainless (iron, chromium, nickel)	Mechanical	*OmniArch Roth®*	GAC International Inc., Bohemia, New York, USA
Ceramic	Polycrystalline (99.9% pure alumina)	Chemo/mechanical	*Allure Roth Ovation®*	

Bonding composites

Details of the adhesives; type, composition, trade name, and manufacture are presented in Table 2.

The tested orthodontic adhesives were light-cured hybrid composite resins; methyl-acrylic bonding systems. But the composition of Transbond XT™ (TB) is based on the molecule Bis-GAM and that of Light Bond™ (LB) is on UDMA. Both are the most frequently used in orthodontic practice and in research.

Light-cure units

Four units from two types of visible light source were used; three light-emitting diode (LED) units and one halogen based. The chosen units were from equipment that could be found in an orthodontist practice. The emission spectrum of these units falls in the same range. The type, light parameters, trade name, and manufacturer are given in Table 3.

The light intensity of each unit was measured with Cure Rite® Light Meter (Dentsply International Inc., Milford, Delaware, USA).

Porcelain surface conditioning was carried out by firstly etching with a 9 per cent solution of HF (Porc Etch™, Reliance Orthodontic Products, Itasca, Illinois, USA) for 3 minutes, rinsed with a water spray for 30 seconds, and dried before silane application. Silane primer RelyX™ (3M ESPE, St. Paul, Minnesota, USA) was applied for further use of Transbond XT™ (TB) composite and the silane Porcelain Conditioner (Reliance Orthodontic Products Inc.) was used in association with Light Bond™ (LB) composite. Both types of silane were allowed to dry for 1 minute.

The sealant of each composite was applied and photo-polymerized for 10 seconds. The paste of TB or LB was applied to the bracket base. The bracket was positioned on the porcelain tab and pressed lightly. Excess adhesive was removed, with a probe and dry microbrush kind sponge-like tip, before light curing for 40 seconds (10 seconds on each side of the bracket). A 0.012 inch ligature wire was tied on the bracket for further use to handle the bracket, from a mid-point of the sample, for tensile tests. All steps were carried out by the same author (NB).

The specimens were stored in water at 37°C for 24 hours. Each specimen was loaded into the Adamel-Lhomargy DY 34 test machine (MTS, Eden Prairie, Minnesota, USA). At a crosshead speed of 5 mm/minute, tensile testing was carried out until bond failure. Tensile bond strength and the mode of bond failure were recorded.

Values of failure loads (*N*) were recorded and converted into Mega-Pascal (MPa) by dividing the failure load (*N*) by the surface area of the bracket base.

The bracket base and the porcelain surface were macroscopically examined using a magnifying glass, by the same author (NB), after bond failure in order to evaluate the mode of failure. Three modes of failure according to the remaining adhesive on each surface were observed:

- Adhesive failure: at the interface bracket–composite (no adhesive on the bracket) or at the interface composite–porcelain (no adhesive on the porcelain);
- Cohesive failure: in one of materials (composite, bracket, or porcelain); and
- Mixed failure: some adhesive remained on the bracket and on the porcelain.

Statistical analysis

The collected data were statistically analysed at a significance level of 0.05 using R language version 2.11.0.

Table 2 The used orthodontic adhesive composites.

Code	Type	Composition	Fillers	Trade name	Manufacturer
TB	Conventional hybrid	Bis-GMA, Bis-EMA, TEGDMA	More than 73–77% silanated quartz and submicron silica	Transbond XT™	3M Unitek, St. Paul, Minnesota, USA
LB	Conventional hybrid	UDMA, TEGDMA, sodium fluoride	85% Fused silica	Light Bond™	Reliance Orthodontic Products, Itasca, Illinois, USA

Table 3 Characteristics of light-curing units and the bulbs. LED, light-emitting diode.

Code	Type	Emission spectrum (nm)	Light intensity (mW/cm^2)	Optical fibre (mm)	Trade name	Manufacturer
EF2	LED1	430–480	1000	8	Elipar™ Freelight 2	3M ESPE, St. Paul, Minnesota, USA
BP	LED2	380–515	1100	8	bluephase®	Ivoclar Vivadent, Schaan, Liechtenstein
SLp	LED3	440–480	600–800	8	starlight pro	Mectron, Carasco, Italia
A10	Halogen	400–510	1200	8	Astralis 10®	Ivoclar Vivadent

For the bond strength, the function lm is used to fit a linear model with normal errors and constant variance. The functional analysis of variance was to select the minimal adequate model. A functional analysis of variance was run to select the minimal adequate model this led to retain a two-way analysis of variance with the two categorical variables; bracket and light.

To analyse the failure model, the type of failure was considered as a categorical response following a multinomial distribution. The function multinom of the nnet R package was used to fit a nominal logistic model with the co-variables; bracket, light, and adhesive.

Results

Tensile bond strength

The mean tensile bond strength and standard deviation for the 16 groups are shown in Table 4.

Starting the statistical analysis by studying the bond strength in function of the three fixed factors: 1. bracket (Metal, Ceramic), 2. adhesive (TB, LB), and 3. light, in an increasing order of 'light intensity' (A10, SLp, EF2, BP), the analysis revealed differences, especially between the two type of brackets. For the light intensity, the analysis showed the halogen A10 and SLP in one side against the LED with higher intensities (EF2 and BP) in the upper side. Then, the analysis of variance, three-way analysis of independent observations with selection of a reference level for each factor was performed to test the saturated model. The metallic bracket was the reference for the factor bracket, the TB for the factor adhesive, and the halogen light A10 for the factor light. The saturated model (Bracket × Adhesive × Light) indicated no main effect 'Adhesive' and all the interactions comprising this factor are insignificant. Therefore, the factor Adhesive was dropped from this model considering a new model (Bracket × Light). The main effects Bracket and Light are significant (both $P < 10^{-5}$). The new model was conserved as the interaction term (Bracket × Light) showed significance ($P = 0.001189$).

By taking the metal bracket and halogen light A10 as reference, with this same bracket there is no significant variation in the mean of force of interaction with the different lights. Conserving the same reference (Metal bracket × A10), for the same light with the ceramic bracket the interaction force increases in average by 2.301 times in a significant way. Changing the light to SLp results in an increase of force in the order of 2.643 times to the reference but not significant related to light change; no significant difference between A10 and SLp. In contrast, with the two other lights, EF2 and BP, the increase in the average force is significant; 4.446 times and 4.014 times, respectively. There is no significant difference between the EF2 and BP.

Table 4 Results of tensile bond strength test for the metal and ceramic bracket: mean values ± standard deviation in MPa.

Bracket system	Metal		Ceramic	
Bonding system / Light cure system	LB	TB	LB	TB
EF2	6.71 ± 1.39	7.10 ± 1.51	11.71 ± 1.72	10.99 ± 1.34
BP	7.30 ± 1.07	6.41 ± 0.99	10.62 ± 1.79	11.12 ± 1.63
SLp	6.45 ± 1.08	6.46 ± 0.94	8.87 ± 1.59	9.32 ± 1.89
A10	6.76 ± 1.25	6.40 ± 0.94	9.11 ± 1.39	8.65 ± 1.53

Bonding Failure model

Table 5 exposes the type of bonding failure observed with metal bracket, and Table 6 shows those with ceramic bracket. The adhesive failure in composite–bracket interface forms 49 per cent and 13 per cent in metal and ceramic brackets, respectively. But the adhesive failure in composite–porcelain interface was the same for both brackets (14 per cent). The metal bracket recorded 38 per cent mixed failure, while the ceramic bracket gave only 0.09 per cent. However, with the ceramic bracket there was 35 per cent failure (fracture) in porcelain and 30 per cent fracture of the bracket itself.

For statistical analysis of the failure mode, the metal and ceramic brackets were studied separately because fracture never occurred in the metal bracket.

At the significance level of 0.05, for the metal bracket, there were no significant differences between the variables, therefore the minimal model was retained; no dependence of the failure rate on the explicative variables. On average and whatever is the combination 'Adhesive × Light', there is a risk to have adhesive only on the porcelain 3.6 times more than having it only on the bracket and 2.7 times risk to have it on both (mixed failure). These results mean that there is 6.3 times more risk to observe residual adhesive on the porcelain and need further surface refinishing to remove it.

For the ceramic bracket, the analysis focused on the failure 'fracture' because of the small effective size in the other failure categories. The selection of the LED SLp as reference light factor was imposed as there is no effective in 'bracket fracture × A10' cells. There was no interaction between the factors 'Light' and 'Adhesive' for the failure 'fracture'. The significant results of the failure mode probability are the following: there is 6 times risk to fracture the porcelain if the adhesive is LB more than the TB, the risk to fracture the porcelain with the light EF is 10 times less than with the light SLp, and if the light SLp and the adhesive TB were used, the probability of porcelain fracture would be in the order of 46 per cent.

Discussion

The findings of this study show that tensile bond strength obtained with ceramic bracket is significantly higher in all

Table 5 Metal bracket: bonding failure model and corresponding samples' number for each light unit and bonding composite.

	Adhesive failure interface composite–bracket		Adhesive failure interface composite–porcelain		Mixed failure	
	LB	TB	LB	TB	LB	TB
FE2	5	4	1	2	4	4
BP	5	2	3	2	2	6
SLp	5	5		1	5	4
A10	6	7	2		2	3
Total for each bonding system	21	18	6	5	13	17
Total for each failure model	39		11		30	

Table 6 Ceramic bracket: bonding failure model and corresponding samples' number for each light unit and bonding composite.

	Adhesive failure interface composite–bracket		Adhesive failure interface composite–porcelain		Mixed failure		Porcelain failure		Bracket failure	
	LB	TB	LB	TB	LB	TB	LB	TB	LB	TB
EF2	1	2	1	3			2		6	5
BP			1	1	1		6	2	2	7
SLp	2		1	1			6	6	1	3
A10	1	4		3	5	1	4	2		
Total for each bonding system	4	6	3	8	6	1	18	10	9	15
Total for each failure model	10		11		7		28		24	

groups tested. These results are in agreement with the findings of Joseph and Rossouw (1990) and Odegaard and Segner (1988). The stronger adhesion with ceramic brackets can be explained principally by joining the chemical retention to the mechanical mode of retention on their base surface (Russell, 2005). Habibi *et al.* (2007) tested the debond strength of ceramic brackets with only one mode of retention, mechanical or chemical, versus metal brackets. In both studies, the debond strength of metal brackets was higher showing that the mode of retention is a principal factor in the higher bond strength of ceramic brackets. A second reason for the higher bond strength of ceramic brackets can be due to their light transmittance allowing for more light availability for photo-polymerization resulting in a higher degree of polymerization (Elekdag-Turk *et al.*, 2007) and reduced stresses in adhesive/bracket interface (Odegaard and Segner, 1988).

There were no significant differences between the bond strength in relation to the used adhesive; Bis-GMA- or UDMA-based composite resins, whatever light source or bracket used. This result differs from these obtained in other studies especially the study of Ozturk *et al.* (2008) on different tooth types using the same adhesives; TB and LB. They found significant changes in shear bond strength with both tooth type and adhesive system. This may be due to the difference between bonding to standard samples of treated porcelain and to tooth enamel with anatomical variations. However, for both adhesives in this study, the minimum bond strength values were higher than 5.1 MPa, which is reported adequate to withstand orthodontic treatment (Cochran *et al.*, 1997; Swanson *et al.*, 2004; Elekdag-Turk *et al.*, 2007; Habibi *et al.*, 2007). Thus, whatever the composition of the adhesive, from the tested category—hybrid with high filler content, it would be suitable for orthodontic bonding on porcelain.

The various light sources with metal bracket did not result in significant difference between the mean bond strengths between the units. While with the ceramic bracket, the bond strength with LED EF2 and BP were significantly higher, each in comparison with the two other units.

This difference, related to light source, between metal and ceramic brackets could be explained by the fact that the translucency of ceramic bracket allow light to pass through more photons resulting in evident influence of light source properties on the quality of composite polymerization as more photons are available for absorption by the photosensitizers (Turkkahraman and Kucukesmen, 2006).

Concerning the differences in the results with ceramic brackets, this could be explained by the following hypothesises:

- EF2 and BP give higher values than SLp, which is also an LED unit with the same range of light emission spectrum.

This is because of the light intensity that is respectively 1000 mW/cm^2 and 1100 mW/cm^2 against 600–800 mW/cm^2 for SLp. According to Turkkahraman and Kucukesmen (2006), 'with high-power LED sources, more photons are available for absorption by the photosensitizers, and with more photons, more camphoroquinone molecules are raised to excited state'. Gritsch *et al.* (2008) have also reported that when the emission spectrum matches with the absorption spectrum of the photoinitiators, the power intensity is the decisive factor.

- EF2 and BP give significantly higher values than A10 because this latter is a halogen LCU. A10 light falls within the optimal emission bandwidth of the light source (400–510 nm) and its intensity is even higher (1200 mW/cm^2) but as shown in many studies, as the major portion of its emitted photons are outside the spectrum range for light cure, these photons cannot be absorbed by camphoriquinone (Swanson *et al.*, 2004; Usumez *et al.*, 2004; Turkkahraman and Kucukesmen, 2006; Gritsch *et al.*, 2008).

Concerning the mode of bonding failure, with metal bracket the failure was more adhesive (63 per cent) with 78 per cent of cases occurred at the interface composite–bracket. Even that it is desirable to have no composite at tooth interface at debonding to facilitate easier bracket replacement and to avoid further cleaning procedure to remove remnant adhesive and possible alteration of tooth/restoration surface (Smith *et al.*, 1988; Ozturk *et al.*, 2008) but having adhesive on tooth/restoration is surely more desirable than getting tooth enamel/porcelain fractured. With the ceramic bracket, adhesive failure occurred in 26 per cent of cases and about half of them occurred at the porcelain interface. The need for further cleaning and adhesive removal was for about 51 per cent of the ceramic bracket cases. These findings are in accordance with the statement of Smith *et al.* (1988) about the usual occurrence, in clinical experience, of having residual composite on porcelain to be refinished with careful removal.

With the metal bracket, no fracture was recorded either in the porcelain or the bracket itself. However, with ceramic bracket, in 30 per cent of the tested samples fracture was within the bracket itself. In addition, the failure of 35 per cent of samples with the ceramic bracket was within the porcelain, whatever the composite or light used. These results for ceramic bracket can be explained by the fact that the rigid brittle nature of the ceramic bracket and the underlying surface as well as the lack of peeling of the bracket from the adhesive during debonding resulted in a poor environment for stress absorption and consequently in high rates of underlying surface fractures and cracks (Russell, 2005; Habibi *et al.*, 2007). Schmage *et al.* (2003) stated that if the shear bond strength between the ceramic and the resin were higher than 13 MPa, the fracture would be cohesive; this could be because the composite resin–porcelain compound is stronger than the ceramic layer itself. This reasoning may explain the higher rate of porcelain fracture when LB adhesive was used by suggesting that it forms a compound with porcelain stronger than that formed by the TB adhesive. Schmage *et al.* (2003) also noted that the incidence of porcelain damage while debonding brackets in clinical practice was very low or did not occur at all. Without excluding the possibility of porcelain fracture in practice, this discrepancy in results can be explained by proper and safe clinical debonding techniques with adequate peeling forces that differ from the testing forces in laboratory (Zachrisson *et al.*, 1996; Schmage *et al.*, 2003). Moreover, in oral cavity and during the treatment, brackets are subjected to a combination of forces; shear, tensile, and torsion and are exposed to the oral environment so they become loose until bond failure occurs (Zachrisson *et al.*, 1996). However, as porcelain fracture cannot be excluded, for clinical consideration and to avoid porcelain damage during bracket removal, Zachrisson *et al.* (1996) suggested grinding away the bracket if it showed resistance.

Conclusions

The findings of this study and within its conditions showed:

- No significant difference between adhesives' composition related to the bonding strength on porcelain.
- Bonding strength of ceramic brackets on porcelain is significantly higher than metal bracket.
- Bonding strength of ceramic bracket is significantly higher when an LED LCU of high light intensity is used compared to halogen-based or LED LCU with low intensity.
- No risk of ceramic fracture when metal bracket or halogen-based LCU is used.
- When a ceramic bracket is used, the risk of porcelain fracture is lesser when using LED LCU of high intensity, and this risk is more probable when using UDMA adhesive with LED LCU of low intensity.

Acknowledgements

We would like to thank all the manufacturers; GAC, Ivoclar Vivadent, Mectron, Reliance Ortho Prod, 3M ESPE and 3M Unitek for providing us with the materials for this study and the information about the products composition when needed.

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