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Evaluation of the debonding strength of orthodontic brackets using three different bonding systems

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SUMMARY The aim of this work was to investigate the stability of the bracket–adhesive–enamel interface, as a function of adhesive material and of debonding procedure, in order to assess which debonding technique is the least detrimental to the enamel. Ninety lower adult bovine incisors were selected and metallic orthodontic brackets were bonded using three adhesive systems: Concise, Transbond, and Fuji Ortho. Three different debonding procedures were used based on tensile, shear, and torsional stresses. One-way analysis of variance statistical analysis was employed to compare mechanical properties, while the adhesive remnant index was used to evaluate fracture properties.

Each adhesive material used showed a statistical difference in tensile failure. The difference between shear and torsion failure loads was statistically significant only for the Fuji GC sample ($P < 0.01$). The shear test was the most damaging to the enamel surface. Transbond luting resulted in greater adhesion than the Concise or Fuji Ortho systems. Fuji Ortho was more prone to accidental debonding, while Transbond tended to cause enamel lesions, since high loads were required to debond the bracket. Of the three modes examined, torsional debonding stress resulted in the least enamel damage.

Introduction

The evolution of multibracket therapy has resulted in a series of advantages, both to the patient and orthodontist. However, accidental debonding of the brackets still remains one of the most frequently encountered problems. Research has mainly concentrated on the reliability of the adhesive systems, on the possibility of reducing enamel damage during bracket removal, and on simplifying adhesive techniques (Bishara *et al.*, 1999). As highlighted by Fox *et al.* (1994) and confirmed by Eliades and Brantley (2000), the protocols used by researchers differ widely. Consequently, comparison of the heterogeneous data is impossible, and clinical inference becomes unreliable. Eliades and Brantley (2000) emphasized the need for a research protocol which standardized a series of parameters and considered all of the variables linked to the operating methodology. In particular, those authors focussed on the influence of the type of substrate used, on the structures of the coupled surfaces, and on the debonding stress methods.

In order to investigate adhesive materials for orthodontic bracket bonding, it is necessary to analyse their performance in relation to the stress involved in the bracket–adhesive–tooth system.

The aim of this research was to determine the mechanical behaviour of the bracket–adhesive–enamel system using three different bonding materials. Three types of mechanical tests were carried out, tensile, shear, and torsion. The debonded surface of each specimen was observed using optical microscopy, and an adhesive remnant index (ARI) analysis was carried out to quantify the amount of adhesive on the enamel surface (Årtun and Bergland, 1984; Cacciafesta *et al.*, 2002; Summers *et al.*, 2004).

Materials and methods

Central lower bovine incisors, which are commonly used for *in vitro* debonding testing (Oesterle *et al.*, 1998; Saleh and Taymour, 2003), were extracted from freshly sacrificed animals with an average age of 2 years (±2 months).

Visual analysis, with ×4 magnification, was carried out in order to select 90 sound teeth, undamaged by the extraction procedures (Figure 1a). The selected teeth were stored in 10 per cent thymol solution at 37°C until sample preparation and mechanical testing was completed. Bonding procedures were undertaken within 1 week of extraction of the teeth.

Further analysis by optical microscopy facilitated the identification and marking of an area with an optimally smooth and flat surface on the vestibular side of each tooth (Figure 1b). The samples were cleaned with pumice (Ruse *et al.*, 1990) and sectioned (Figure 1c) with an Isomet microtome (Buehler Ltd, Lake Bluff, Illinois, USA), fitted with a diamond saw (0.3 mm thick and 100 mm diameter) and cooled by water at a speed of 125 mm/second (150 rpm). The sections were then placed on an adhesive tape (Figure 1d) and embedded into steel cylinders (Figure 1e,f) filled with a self-curing, methyl methacrylate-based resin (Formatray, Kerr Corporation, Orange, California, USA). Again, visual analysis was used to select specimens

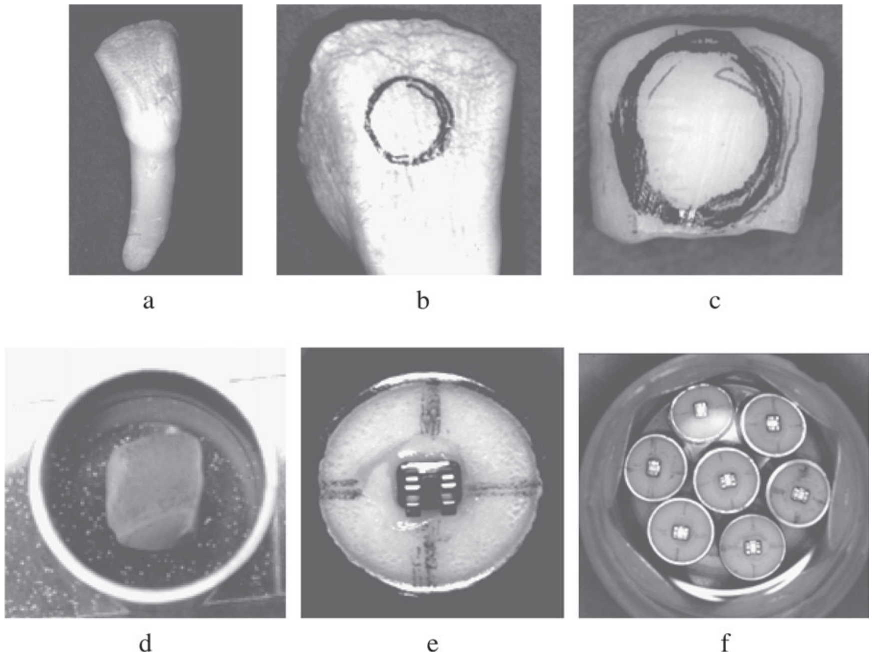

Figure 1 Specimen preparation: (a) selection of 90 sound teeth, undamaged by the extraction procedure; (b) marking of an almost smooth and flat surface on the vestibular side; (c) magnification of the area of interest cleaned with pumice; (d) positioning of the specimen on adhesive tape; (e) cementing of the specimen with poly(methyl methacrylate) and bracket bonding; and (f) sample storage.

without damage (i.e. enamel fractures) due to fixation procedures.

Preparation of the specimens

The 90 teeth were randomly divided into three equal groups. The metal brackets used were OmniArch Ricketts model (GAC International Inc., Bohemia, New York, USA) for upper central incisors (slot dimensions 0.018 × 0.030 inch), having a fairly flat base with a half-dome mechanical retention.

In group A, a glass-ionomer cement modified with light-activated resin (Fuji, GC America Inc., Alsip, Illinois, USA) was used; in group B, the brackets were bonded with a chemically activated paste–paste composite (Concise, 3M Unitek, St Paul, Minnesota USA); and in group C, a light-activated composite was used (Transbond, 3M Unitek). The technical specifications of all materials are reported in Table 1.

For group A specimens, the enamel surface was conditioned with 10 per cent acrylic acid solution for 15 seconds and then rinsed for 30 seconds. The surface was kept in a humid environment during the application of the cement, previously stirred for 10 seconds. A 300 g weight was then placed on the bracket base for 15 seconds and excess cement was carefully removed. The adhesive was cured for 40 seconds using a halogen light source with a power output of 800 mW/cm^2 (Optilux, Demetron, Kerr Corporation). The output of the curing unit was periodically controlled by a radiometer (Demetron Corporation) with 900 mW/cm^2 full scale.

For group B specimens, the enamel surface was conditioned with 37 per cent orthophosphoric acid for 45 seconds, then rinsed for 30 seconds and dried with an oil-free air jet. The adhesive resin and the composite paste were applied to the enamel surface and to the bracket base,

Table 1 Adhesive materials used to bond brackets.

Commercial Name	Adhesive Type	Polymerise system	Manufacture	Lot#
Fuji-Ortho LC	Glass-ionomer cement modified with light cured resin	Dual (chemical and light) polymerization	GC America Inc.	Lot 020291
Concise	Bis-GMA resin	Chemical polymerization	3M Unitek	Paste A N° 1961A; Paste B N° 1961B; Resin A; N° 1922A Resin B N° 1922B; Etching 1923
Transbond XT	Bis-GMA resin	Light polymerization	3M Unitek	REF 77-111-70 M-P OMNI Lot 1199

respectively. As in group A, each bracket was preloaded with a 300-g weight.

For the Transbond samples (group C), the enamel was etched with 37 per cent orthophosphoric acid for 15 seconds, rinsed for 30 seconds, and carefully dried with an oil-free air jet. The adhesive resin was applied to the enamel surface, and the composite resin to the base of the bracket. Each bracket was then preloaded, as in group A. After removing the composite cement excess, curing was then effected by exposure to the halogen light source for 40 seconds.

Mechanical tests

Each group of specimens was divided into three subgroups of 10 samples for mechanical characterization of tensile, shear, and torsion values.

Tensile tests were carried out using an Instron 4204 screw driven dynamometer (Instron, High Wycombe, Bucks, UK). The crosshead speed was set at 0.5 mm/minute and a 1 kN load cell was used. The samples, gripped into the chuck of the testing dynamometer, were stressed using a suitable stainless steel tool (Figure 2a). Shear and torsion tests were carried out using a servohydraulic dynamometer MTS 858 Bionix (MTS, Minneapolis, Minnesota, USA), using a load cell with load and torque ranges of 2.5 kN and 25 Nm, respectively. The shear tests were undertaken in a displacement control with the activator speed set at 0.5 mm/minute. The load was applied to the longer side of the bracket base using a knife-blade (Figure 2b). The torsion tests were carried out controlling the angular position and with the angular speed set at 0.5 degrees/minute. Torque was applied through a flat (2.7 mm thick) screwdriver placed in the vertical groove between the wings of the bracket (Figure 2c). The data acquisition (load, torque, and axial and angular position) was undertaken at a speed of 10 points/second.

The statistical significance of the results was assessed using one-way analysis of variance (ANOVA; Cheremisinoff, 1987) through the Origin® 6.0 package (Microcal Software, Northampton, Massachussets, USA). Confidence levels of 99 and 95 per cent were set for mechanical strength and ARI, respectively.

Analysis of fractured surfaces

Analysis of the fractured surfaces, externally illuminated by an optical fibre, was performed using a Zeiss optical microscope (Carl Zeiss IMT Corporation, Minneapolis, Minnesota, USA) at ×20 magnification. For each sample, the amount of composite adhering to the enamel substrate was quantified using the ARI (Årtun and Bergland, 1984; Cacciafesta *et al.* 2002; Summers *et al.*, 2004). A score of 1 was assigned when all the composite remained on the enamel surface and a clear imprint of the bracket was evident; 2, when more than 90 per cent of the composite was present on the surface; 3, when 10–90 per cent of the composite remained on the surface; 4, when less than 10 per cent of the composite remained; and 5, when no composite remained on the enamel surface, i.e. where there was complete transfer of composite to the bracket base.

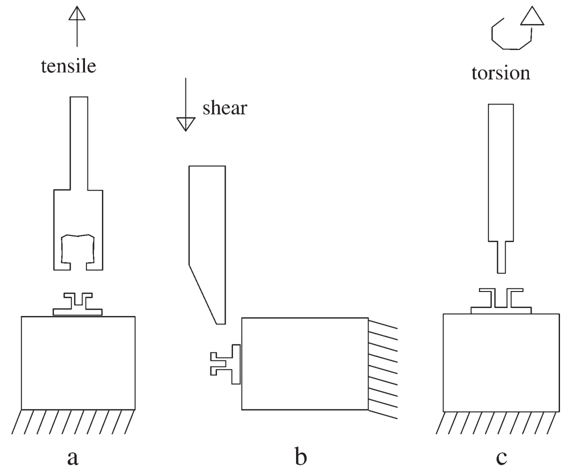

Figure 2 Mechanical testing scheme: (a) tensile test showing the stainless steel tool used to load the bracket–adhesive–enamel system through the bracket wings; (b) shear test showing the knife-blade loading the bracket on the longer side of the base; and (c) torsion test depicting the screwdriver used to load the bracket through the vertical groove between the wings.

Results

Typical load–displacement curves in tension related to each adhesive system are presented in Figure 3. Groups A, B, and C showed a failure load of 60 N [standard deviation (SD) 17], 114 N (SD 14), and 200 N (SD 12), respectively. For tensile testing, the statistical comparison (Cheremisinoff, 1987) between the failure loads using the *F*-test and the level of probability (*P*) showed that there were significant differences between the three bonding materials. In particular, the difference between the distributions of the maximum loads of groups A and B was represented by $F = 17.3$ and $P = 1.9 \times 10^{-3}$, while that between groups A and C was $F = 75.3$ and $P = 1.15 \times 10^{-5}$ and finally the difference between group B and C was $F = 12.4$ and $P = 4.8 \times 10^{-3}$. Therefore, a significant difference was identified between groups A, B, and C.

Typical shear load–displacement is shown in Figure 4. For shear testing, the difference between the failure loads of groups A and B was statistically significant ($F = 23.3$ and $P = 7.0 \times 10^{-4}$). A similar result was observed when comparing groups A and C ($F = 21.9$ and $P = 1.1 \times 10^{-3}$), but no statistical difference was found between groups B and C ($F = 1.18$ and $P = 0.29$).

Typical torque–rotation is shown in Figure 5. In torsion testing, the difference between the failure torque of groups A and B was statistically significant ($F = 12.4$ and $P = 4.8 \times 10^{-3}$). A significant difference was also observed

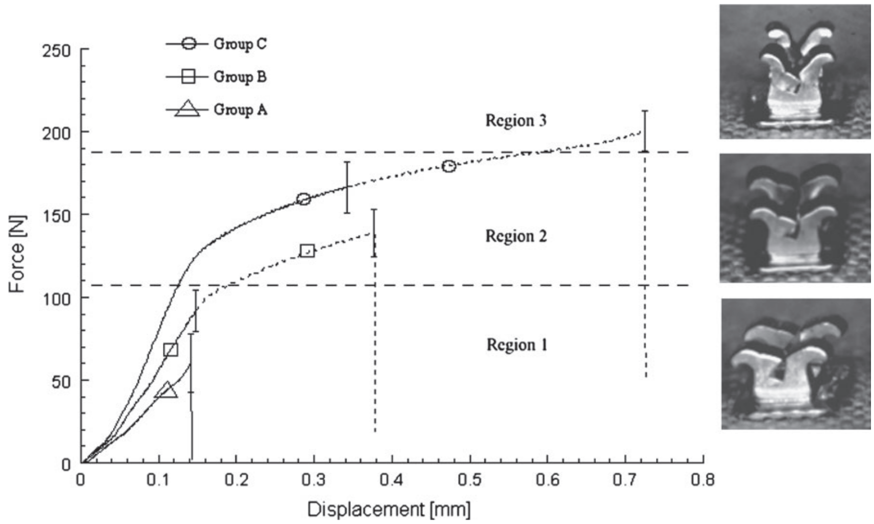

Figure 3 Load versus displacement of the tensile test. Three distinct regions can be identified: in region 1, the wings behave elastically; in region 2, a plastic deformation of the wings is observed from the decrease of the slope of the force–displacement curve at about 100 N; in region 3, the wings converge by increasing the load until complete closure of the slot is detected and an increase of the slope is clearly observed.

between groups A and C ($F = 15.5$ and $P = 3.4 \times 10^{-3}$), while a weaker statistical difference was found between groups B and C ($F = 4.9$ and $P = 0.05$).

The values of the ARI index for the three groups according to the type of mechanical test are depicted in Table 2. One-way ANOVA testing showed that there was a statistically significant difference in retention between groups A and B ($P < 0.05$) and between groups A and C ($P < 0.05$). The ARI values obtained from the shear tests indicated that the statistical difference was limited to groups A and B ($P < 0.05$), while the torsion test did not show a significant difference between the three materials. These data suggest that the application of a torsional moment resulted in a similar type of fracture, regardless of the adhesive material used. Furthermore, analysis of the fracture surfaces by optical microscopy confirmed the absence of enamel lesions in all of the samples debonded by torsion.

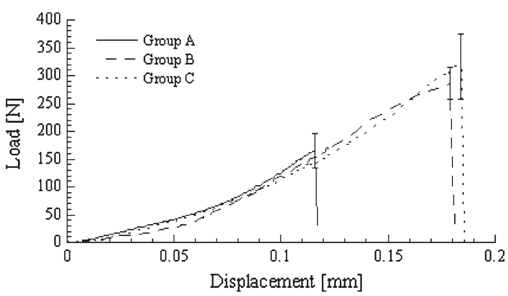

Figure 4 Load versus displacement during shear testing. A similar trend is observed for each group. Group A specimens had the weakest shear debonding loads. The error bars represent the standard deviation of the failure loads.

Discussion

In tensile, shear, and torsion tests, the specimens can be considered as a series of bracket–adhesive–enamel: the load is the same for each element of the series, stainless steel, polymer composite, and enamel substrate, while the value of deformation for each element of the series is different. The deformation, i.e. the axial and angular displacement, as shown in Figures 3 and 5, is, in each case, the sum of the contributions of the single elements. For this reason, comparative statistical analysis is appropriate only regarding

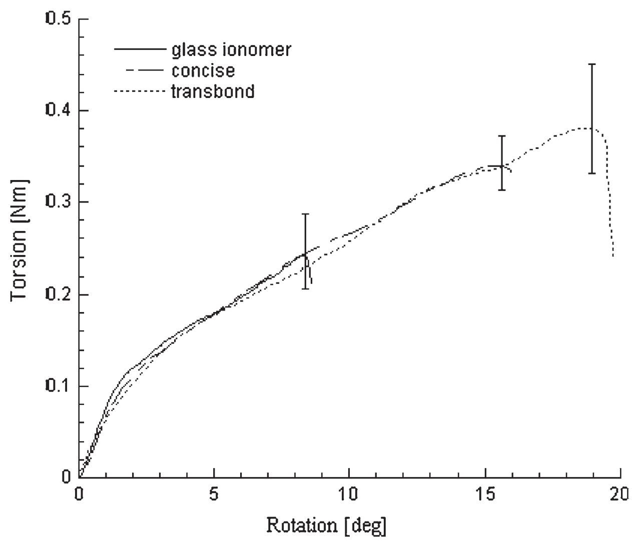

Figure 5 Torsion versus angular displacement. Two distinct regions may be identified: in region 1, the wings behave elastically while in region 2 plastic deformation of the wings is observed. Group A specimens have the weakest torque debonding loads.

Table 2 Adhesive rannant index mean values of each group (A, Fuji Ortho; B, Concise; and C, Transbon) according to mechanical debonding mode. Numbers in brackets represent the standard deviation.

	Tensile	Shear	Torsion
Group A	3.3 (1.4)	4.2 (0.4)	4.0 (0.9)
Group B	2.0 (0.7)	2.8 (0.7)	3.0 (0.8)
Group C	1.5 (1.3)	3.8 (0.5)	3.0 (0.8)

the failure loads of each sample. In particular, in the tensile and torsion tests (Figures 3 and 5), the samples with the Transbond adhesive (group C) reached loads that deformed the wings of the bracket. Therefore, this deformation quota characterizes the total deformation of the system (group C; Figure 3). The wing deformation of the bracket is clearly evident from the decrease of the slope of the force–displacement curve at about 100 N, where plastic deformation of the wings started to occur (region 2; Figure 3). In group C, the wings converge with increasing load, up to complete closing of the slot (Figure 3c). At this point, an increase of the slope was detected (region 3; Figure 3).

The results indicate a statistically significant difference between the tensile debonding loads of the adhesive systems investigated. Group C showed the highest debonding value, while group A exhibited the weakest tensile debonding load. The tensile load required to debond group A brackets (Figure 3) and the related ARI score (Table 2) are close to the values measured by Algera *et al.* (2005). It is interesting to observe that the ARI score indicates that acid etching of the substrate (group C) improves the retention of the adhesive material on the enamel. This result is consistent with finding of Abu Alhaija and Al-Wahadni (2004).

There was a statistically significant difference between the shear debonding loads of groups A and B ($P < 0.01$), as well as between those of groups A and C ($P < 0.01$). Fuji GC showed the weakest shear debonding load, while no difference was observed between groups B and C. Again, there was a significant statistical difference between the torsional debonding loads observed for groups A and B ($P < 0.01$), and when comparing values for groups A and C ($P < 0.01$). The results showed that Fuji GC had the weakest bonding capability. This result is consistent with adhesive shear strength reported by Movahhed *et al.* (2005). However, if shear stress is extrapolated by dividing the shear force by the bracket base, values of 14 and 26 MPa were obtained for groups A and C, respectively. These values are higher than those found by Movahhed *et al.* (2005) who used the same adhesive materials. This difference can be ascribed to two main aspects: the duration of the conditioning which in the present protocol was longer, and the application of a load of 300 g on the bracket during bonding.

It is suggested that mechanical properties of light-cured composites undergo a transitory change (Versluis *et al.*, 2004), i.e. the mechanical properties significantly increase with time until a plateau is reached. In addition, the adhesive used to bond brackets to enamel also undergoes transient change in properties. The findings of Wendl and Droschl (2004) clearly show that the strength of directly bonded brackets increases during the first 24 hours. Consequently, the measurements in the present investigation were performed after 24 hours, and the recorded values were higher than those reported by other authors who used shorter conditioning periods (Cacciafesta *et al.*, 2002; Movahhed *et al.* 2005). Despite the different testing protocols, the ARI values related to the shear tests of groups A and C (Table 2) are consistent with the findings of Cacciafesta *et al.* (2002) and Movahhed *et al.* (2005).

With the bracket–adhesive–tooth system, the metal bracket is the least critical variable. Accordingly, in accidental debonding which may occur during orthodontic treatment, the fracture pattern is generally localized at the level of the enamel–composite interface (Lopez, 1980). In clinical practice, the choice of a bonding system is based upon the adhesion capability of the material as well as the handling procedure (Regan and Van Noort, 1989). For example, light-curable materials such as Transbond combine high adhesion values with easy handling, virtually unlimited positioning time, and, therefore, high positioning accuracy. Moreover, the retentive characteristics of bracket bases have evolved to such a level that, usually, a fracture at the composite–bracket interface is uncommon in clinical trials (Smith and Maijer, 1983). Rather, such fractures tend to occur at the enamel–composite interface and are almost always caused by errors in operating procedures or in the manipulation of the adhesive materials (Maijer and Smith, 1981). Indeed, when these materials are used correctly, the adhesion values attained are so high that they may cause enamel lesions during debonding. As noted previously, plastic deformation of the wings of the brackets of groups B and C was commonly observed, indicating a strong mechanical interface.

Identification of debonding methods which are less detrimental to the enamel surface should, therefore, be a key objective of research in this area. Regan and Van Noort (1989) showed that higher debonding strength values are obtained when brackets are subjected to shear rather than to tensile stresses. Thus, in clinical practice, it would be better to apply tensile loads in the debonding phase. In the present study, torsion stress resulted in less loading being required for debonding with torque debonding values (Figure 5) ranging from 0.2 to 0.4 Nm. Consequently, when using a lever with a length of 1 cm, a load between 20 and 40 N would be required to debond the bracket. In addition, debonding by torsional stress was the least damaging to the enamel.

Groups A and C specimens were cured using an 800 mW/cm^2 halogen lamp, which is the most widely used type of light source for this application. Although the degree of conversion of a photo-cured composite is expected to be dependent upon the light source, Cacciafesta *et al.* (2001) suggested that there was no statistically significant variation in debonding stress with different light sources, at least when quartz-halogen or xenon lamps were used. In the current research, therefore, the hypothesis was that bonding strength is independent of the light unit. Moreover, the light energy dose supplied in 40 seconds is sufficiently high, at 32 J/cm^2, to consider the composite material to be adequately cured (Musanje and Darvell, 2003).

This research clearly demonstrates that, as far as debonding procedures are concerned, both material and mechanical stress must be considered. Tensile testing showed that the Transbond adhesive system was the most resistant (Fmax = 68.6 ± 15.7 N). Furthermore, the weakest interface in the sample was between bracket and adhesive, as confirmed by an ARI score of 1.63. This indicates that most of the material remained attached to the enamel surface. In contrast, shear testing resulted in fractures occurring mainly at the enamel–adhesive interface. Using optical microscopy of the dental surface after debonding of the bracket, small cohesive fractures of the enamel were observed. This type of stress, *in vitro*, therefore seems to be most damaging to the enamel surface.

High strength values were achieved with Concise and Transbond, while Fuji always showed lower adhesion (Figures 3–5). Torsion testing gave more consistent data for debonding strengths. This emphasizes the importance of investigating a system by a variety of methods, in order to understand to what extent the type of mechanical test used influences the behaviour of the system.

Comparing the effects of the shear and torsion tests (Figure 2b,c), torsion was least damaging to the enamel (Table 2). Currently, the debonding of brackets is carried out using unstandardized procedures, with many variable parameters. Forces that are uncalibrated, in terms of intensity and direction, are applied in an uncontrolled manner. This means that debonding tests that exclusively use only one type of force (i.e. shear, torsion or, tensile) are not clinically relevant.

Conclusions

The results of this research have highlighted some clinical considerations. It is necessary to identify the optimum procedure for the preparation of the bonding material and the type of stress which, together, prove to be the least detrimental to the enamel during debonding. In clinical practice, the stresses applied on the brackets during debonding are a combination of tensile, shear, and torsion forces. The tests used in the present study indicate that torsional stresses result in the least enamel damage.

The methods used for mechanical debonding tests are easy to set up and provide reliable results. The Transbond luting system gave higher adhesion values compared with Concise and Fuji Ortho.

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References

Abu Alhaija E S, Al-Wahadni A M S 2004 Evaluation of shear bond strength with different enamel pre-treatments. European Journal of Orthodontics 26: 179–184

Algera T J, Kleverlaan C J, de Gee A J, Prahl-Andersen B, Feilzer A J 2005 The influence of accelerating the setting rate by ultrasound or heat on the bond strength of glass ionomers used as orthodontic bracket cements. European Journal of Orthodontics 27: 472–476

Årtun J, Bergland S 1984 Clinical trials with crystal growth conditioning as an alternative to acid-etch pretreatment. American Journal of Orthodontics 85: 333–340

Bishara S E, Gordan V V, VonWald L, Jakobsen J R 1999 Shear bond strength of composite, glass ionomer, and acidic primer adhesive systems. American Journal of Orthodontics and Dentofacial Orthopedics 115: 24–28

Cacciafesta V, Sfondrini M F, Klersy C, Sfondrini G 2002 Polymerization with a micro-xenon light of a resin-modified glass ionomer: a shear bond strength study 15 minutes after bonding. European Journal of Orthodontics 24: 689–697

Cacciafesta V, Sfondrini M F, Sfondrini G 2001 Fotopolimerizzazione ad alta densità di un adesivo ortodontico mediante lampada al micro-xenon. Ortognatodonzia Italiana 10: 301–306

Cheremisinoff N P 1987 Practical statistics for engineers and scientists. Technomic Publishing Company Inc., Lancaster, pp. 71–112.

Eliades T, Brantley W A 2000 The inappropriateness of conventional orthodontic bond strength assessment protocols. European Journal of Orthodontics 22: 13–23

Fox N A, McCabe J F, Buckley J G 1994 A critique of bond strength testing in orthodontics. British Journal of Orthodontic 22: 33–43

Lopez J I 1980 Retentive shear strengths of various bonding attachment bases. American Journal of Orthodontics 77: 669–678

Maijer R, Smith D C 1981 Variables influencing the bond strength of metal orthodontic bracket bases. American Journal of Orthodontics 79: 20–34

Movahhed H Z, Øgaard B, Syverud M 2005 An *in vitro* comparison of the shear bond strength of a resin-reinforced glass ionomer cement and a composite adhesive for bonding orthodontic brackets. European Journal of Orthodontics 27: 477–483

Musanje L, Darvell B W 2003 Polymerization of resin composite restorative materials: exposure reciprocity. Dental Materials 19: 531–541

Oesterle L J, Shellhart W C, Belanger G K 1998 The use of bovine enamel in bonding studies. American Journal of Orthodontics and Dentofacial Orthopedics 114: 514–519

Regan D, Van Noort R 1989 Bond strengths of two integral bracket-base combinations: an *in vitro* comparison with foil-mesh. European Journal of Orthodontics 11: 144–153

Ruse N D, Smith D C, Torneck C D, Titley K C 1990 Preliminary surface analysis of etched, bleached and normal bovine enamel. Journal of Dental Research 69: 1610–1613

Saleh F, Taymour N 2003 Validity of using bovine teeth as a substitute for human counterparts in adhesive tests. East Mediterranean Health Journal 9: 201–217

Smith D C, Maijer R 1983 Improvements in bracket base design. American Journal of Orthodontics 83: 277–281

Summers A, Kao E, Gilmore J, Gunel E, Ngan P 2004 Comparison of bond strength between a conventional resin adhesive and a resin-modified glass ionomer adhesive: an *in vitro* and *in vivo* study. American Journal of Orthodontics and Dentofacial Orthopedics 126: 200–206

Versluis A, Tantbirojn D, Douglas W H 2004 Distribution of transient properties during polymerisation of a light-initiated restorative composite. Dental Materials 20: 543–553

Wendl B, Droschl H 2004 A comparative *in vitro* study of the strength of directly bonded brackets using different curing techniques. European Journal of Orthodontics 26: 535–544