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Development of a device to measure bracket debonding force *in vivo*

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SUMMARY The purposes of this study were to develop a device to measure bracket debonding force *in vivo* and to evaluate, *in vitro*, the bond strength obtained with the device and with tensile and shear bond strength (SBS) tests performed in a universal testing machine.

The device was developed using polypropylene pliers (3M Unitek). The basic principle consisted of measuring the applied force to debond, using two strain gauges (Kyowa) bonded to the region of major deformation of the plier handles. The crowns of 75 bovine incisors were embedded in acrylic resin and orthodontic brackets were bonded to the facial surface with Transbond XT (3M Unitek). In group A ($n = 25$) debonding was carried out with the device, while tensile bond strength testing was performed in group B ($n = 25$) and SBS testing in group C ($n = 25$). A universal testing machine (EMIC-DL-2000) was used for these last two groups.

According to analysis of variance and Tukey's test ($\alpha = 0.05$), the mean bond strength for group C (7.71 MPa) was statistically higher than for groups A (2.98 MPa) and B (2.69 MPa). Groups A and B were not statistically different.

The device was shown to be feasible to obtain *in vivo* bond strength values for orthodontic brackets, and that the bond strength values were dependent on the method and direction of debonding.

Introduction

Direct bracket bonding to dental enamel has been extensively studied due to the biomechanical importance of a stable interface between the bonding material and the bracket, as well as between the bonding material and the enamel, so that the loads generated by fitting an activated arch may be transferred to the teeth (Eliades and Brantley, 2000).

These interfaces and the force required to debond the brackets from the tooth enamel have been assessed, *in vitro*, by means of tensile (Siomka and Powers, 1985; Fajen *et al.*, 1990) or shear (Smith and Shivapuja, 1993; Arnold *et al.*, 2002) strength tests using universal testing machines. These machines allow high precision tests to be performed and, irrespective of the brand and model, are large, expensive, and complex to handle. However, due to their proportions, they make it impossible for *in vivo* studies to be carried out (Hubert *et al.*, 2001).

There is a complex interaction process in the oral cavity that cannot be completely reproduced *in vitro* (Oilo, 1992; Eliades *et al.*, 1999). Exposure of dental materials to the oral medium is associated with an ageing pattern, which may alter the composition and the mechanical properties of the orthodontic alloys and polymers (Eliades and Bourauel, 2005). According to Oilo (1992), biodegradation is the combined result of disintegration and dissolution in saliva, chemical and physical degradation, wear caused by mastication, and erosion caused by food and bacterial activity. Matasa (1995) proposed that material biodegradation may contribute to the lack of bonding between the bracket and the tooth. As a result of biodegradation, Pickett *et al.* (2001) and Murray and Hobson (2003) found that bond strength values *in vivo* tend to be lower than those observed *in vitro* and highlighted the necessity of creating a method to test the effects of the oral medium on the composite resins used in orthodontics. In addition, Sunna and Rock (1998) concluded that *in vitro* bond strength cannot be correlated with clinical failure indices and questioned the applicability of these tests to the clinical situation.

Since the majority of studies have been laboratory based, and as differences exist between *in vitro* studies and the clinical situation, it is difficult to establish the clinical bond strength values required for an adequate bond between the bracket and the tooth element.

The aim of the present study was to develop a device to measure bracket debonding force *in vivo*. The bond strength obtained with the device was compared *in vitro* with that obtained by means of tensile and shear bond strength (SBS) tests in a universal testing machine.

Materials and methods

Development of the device

The electro-electronic instrumentation of Polypropylene pliers (Debracketing Instrument 444-761, Instrument kit, 3M/Unitek, Monrovia, California, USA), to measure

bracket debonding force, was developed in the Instrumentation and Measurement Laboratory of the Mechanical and Mecatronic Engineering Department of the Engineering School at Pontifical Catholic University of Rio Grande do Sul, Brazil.

The working principle of the pliers consists of measuring the force applied to the active arm of the pliers by measuring the deformation of this arm. Initially five holes, 2 mm in diameter, were made with a 2 mm low speed drill in the top one-third of the active arm lateral surface. The anterior and posterior two-thirds at the surfaces of the active arm were metal coated with a composition of iron filings and cyanoacrylate. These surfaces were cleaned with isopropyl alcohol and two Constantan electrical resistance strain gauges (45 per cent Ni; 55 per cent Cu) with 10 mm of sheet-type grid, and temperature compensation for steel (Kyowa, Chofu, Tokyo, Japan) were bonded to the metal-coated surfaces with cyanoacrylate ester-based adhesive (Loctite, São Paulo, Brazil). One strain gauge was bonded to the face of the anterior active arm of the pliers and the other to the posterior face, both in the longitudinal direction. After bonding, the strain gauge wires were welded to the Wheatstone half-bridge-type circuit. For protection, a layer of silicone, without acetic acid, was applied around the strain gauges (Figure 1). The tension generated by the strain gauges from the deformation of the plier levers was multiplied by an amplifier circuit, composed of an integrated INA 101HP circuit (Texas Instruments, Thief River Falls, Minnesotta, USA). This generated the signal for an ATMEGA 8 microprocessor (Atmel Corporation, San Jose, California, USA), which displayed the values already converted into kgf (kilogram force) in a real time. Device calibration consisted of three adjustments: (1) balancing the bridge of the strain gauges (Wheatstone bridge-type circuit in the half-bridge configuration because of two resistances and two strain gauge being used); (2) amplifier gain; and (3) off-set of the amplifier outlet.

Device gauging procedure

To evaluate the developed device, the following weights were used: 1, 2, 3, 4, 5, 6, and 7 kg. To ensure that the pliers remained in the same position at all times during measuring, they were fixed in a bench lathe. In a plastic plate with an internal diameter of 18 and 3 cm height, three equidistant holes were made in the lateral part, in which 0.30 mm diameter and 50 cm long stainless steel wires were tied and joined to a hook with 0.70 mm diameter stainless steel wire, which was fitted into the bracket fixing claw of the debonding pliers. The measurements were undertaken by two assessors (AMS—assessor A, JRP—assessor B). The assessors standardized the position of the hand on the pliers, so that the fore, middle, ring, and little fingers were placed along the active arm and the thumb on the fixed arm. Each weight was placed on the plastic plate, the display was zeroed, and the measurement was then carried out by displacing the active arm and lifting the weight (Figure 2). Twenty repetitions were performed for each weight. The numerical value recorded on the display was noted and at the end of the 20 readings, the arithmetic mean was calculated. The mean temperature in the laboratory during the experiments was 26.5°C and the humidity 70 per cent.

Test specimen preparation

The crowns of 75 permanent bovine incisor teeth were sectioned at the superior and inferior thirds, to obtain 10 mm high coronary portions. The coronal portions were placed with the vestibular face against adhesive tape fixed

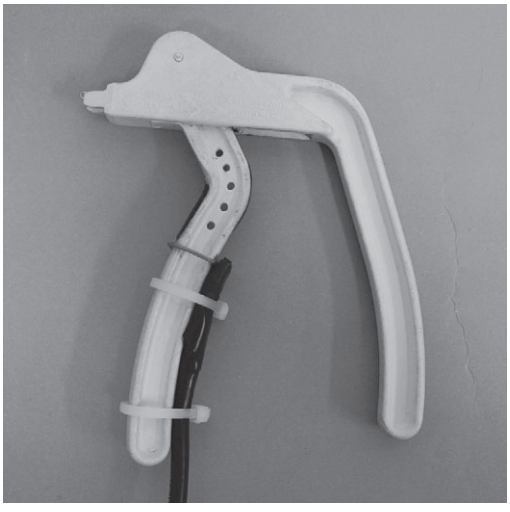

Figure 1 Polypropylene pliers with the five holes in the top one-third of the active arm lateral surface; strain gauges are bonded to the anterior and posterior active arm face of the pliers.

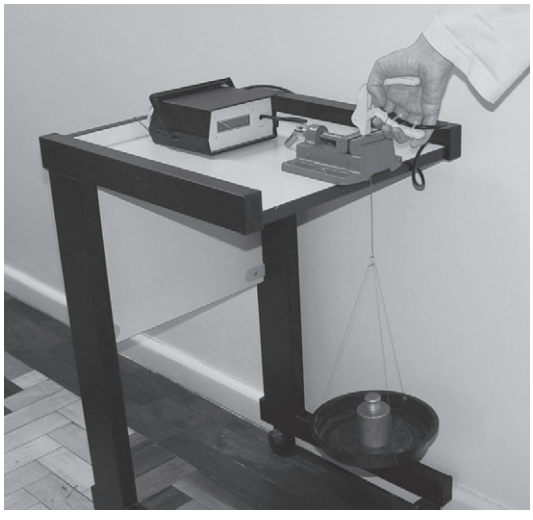

Figure 2 The pliers fixed in a bench lathe and the weight placed in the plastic plate.

on a flat surface. A Polyvinyl chloride ring (20 mm diameter, 20 mm height) was placed on the adhesive tape so as to surround the entire tooth fragment, and self-cured acrylic resin was poured onto it. The exposed enamel surface was lightly abraded with 400 and 600 grain silicone carbide abrasive papers in a DPU-10 polisher (Panambra, São Paulo, Brazil), under constant water irrigation to obtain a flat enamel surface. The maxillary central incisor brackets (reference 10.30.201, Morelli®, Sorocaba, São Paulo, Brazil) were bonded to the enamel surface using the following procedure: (1) prophylaxis with pumice stone and water for 10 seconds; (2) washing with water for 10 seconds; (3) drying with an air jet for 10 seconds, at a distance of 50 mm; (4) etching with 37 per cent phosphoric acid for 15 seconds, followed by washing and drying; (5) application of Transbond XT adhesive (3M/Unitek) on the etched enamel; (6) application of Transbond XT composite resin on the bracket base and positioning on the tooth with light manual pressure, followed by removal of the excess adhesive with an exploratory probe; and (7) light curing of the composite resin for 40 seconds (10 seconds on each face) with the Optilight Plus appliance (Gnatus, Ribeirão Preto, Brazil). The light intensity was controlled by a radiometer (Demetron/Kerr, Danbury, Connecticut, USA), remaining between 470 and 500 mW/cm^2. All bonding was carried out by the same operator (JRP). The test specimens were stored in a closed receptacle with 100 per cent relative humidity at 23°C for 1 hour and then immersed in distilled water at 37°C for 23 hours.

Bracket debonding trial

The 75 test specimens were divided into three equal groups. In group A, debonding was undertaken using the developed device. For group B, tensile testing was carried out and in group C shear testing, both in a universal testing machine.

Group A—bracket debonding with the developed device. Each test specimen was placed in a bench lathe. A single operator (JRP) held the pliers in the same position at all times. The pliers were placed on the bracket with the supports aligned in an occluso-gingival direction in contact with the enamel. With the claw hitched onto one of the bracket wings, the pliers were activated by moving the active arm until bracket debonding occurred. The force necessary to remove the bracket was recorded on the display in kgf, transformed into Newtons, and divided by the bracket area (14.12 mm^2), to obtain resistance values in megapascal (MPa).

Group B—bracket debonding by tensile testing in a universal testing machine. The test specimen was fixed in a metal sleeve on the bottom part of the universal testing machine EMIC-DL-2000 (EMIC São José dos Pinhais, São Paulo, Brazil). For tensile testing, a hook made of stainless steel wire (diameter 0.40 mm, length 5 cm) was connected to one of the bracket wings. A 2 mm thick and 20 mm long wire segment was welded to the top part of the hook, which was hitched onto the top part of the universal testing machine. The crosshead speed was 0.5 mm per minute until bracket debonding occurred. The resistance value was obtained in MPa, as described for group A.

Group C—bracket debonding by shear testing in a universal testing machine. The test specimen was fixed in a metal sleeve on the bottom part of the universal testing machine. For shear testing, a chisel with a guillotine system and a 2 mm thick contact face with the bracket was used. The crosshead speed was 0.5 mm per minute until bracket debonding occurred. The resistance value was obtained in MPa, as described for groups A and B.

Fracture-type analysis

After bond strength testing, all specimens were visually examined with a stereomicroscope (Olympus Corp., Tokyo, Japan) at x10 magnification to assess the fracture pattern and Adhesive Remnant Index (ARI; Årtun and Bergland, 1984): score 0, no composite resin left on the tooth; score 1, less than half of the composite resin left on the tooth; score 2, more than half of the composite resin left on the tooth; score 3: all composite resin left on the tooth, with distinct impression of the bracket mesh.

Statistical analysis

Analysis of variance (ANOVA) and Tukey multiple comparison tests ($\alpha = 0.05$) were performed to compare the groups. For comparison between the assessors, the Student's *t*-test ($\alpha = 0.05$) for paired samples was used. A Kruskal–Wallis test ($\alpha = 0.05$) was used to analyse the fracture types. The data were processed and analysed using Statistical Package for Social Sciences, version 10.0 (SPSS Inc, Chicago, Illinois, USA).

Results

ANOVA revealed significant differences among the groups ($P < 0.05$; Table 1). According to Tukey multiple comparison test (Table 2), the highest mean bond strength was for group C (7.71 MPa). This was statistically different and significantly greater than the other groups. The mean bond strength. For groups A (2.98 MPa) and B (2.69 MPa) were statistically similar.

Table 3 shows the mean values obtained by the two assessors, for each weight, during gauging of the device. According to the Student's *t*-test, there were significant differences ($P < 0.05$) between the examiners at 2, 3, 5, and 6 kg weights, the values being higher for assessor A. For both assessors, the developed device recorded grams above the weight being used.

An ARI score of 3 was predominant in all groups. There was no statistical difference (Kruskal–Wallis, $P > 0.05$) between the groups (Table 4).

Table 1 Analysis of variance.

Variation	Sum of squares	Degrees of freedom	Mean square	*F*	*P*
Between groups	397.67	2	198.83	58.25	<0.05
Within groups	245.75	72	3.41		
Total	643.42	74			

Table 2 Comparison of mean bond strength (MPa) obtained for each group.

Groups	*n*	Mean	Standard deviation	*P*
Group A	25	2.98[A]	0.32	<0.05*
Group B	25	2.69[A]	0.40	
Group C	25	7.71[B]	3.16	

Group A, developed device.
Group B, tensile testing in a universal testing machine.
Group C, shear testing in a universal testing machine.
*Different letters indicate statistically different mean values ($P < 0.05$).

Table 3 Comparison between the assessors for each weight.

Comparison	*n*	Mean (Kgf)	Standard deviation	*P*
1 kg assessor A	20	1.72	0.08	0.21
1 kg assessor B	20	1.76	0.12	
2 kg assessor A	20	2.46	0.14	0.01*
2 kg assessor B	20	2.26	0.19	
3 kg assessor A	20	3.30	0.16	0.01*
3 kg assessor B	20	3.04	0.27	
4 kg assessor A	20	4.44	0.26	0.48
4 kg assessor B	20	4.37	0.35	
5 kg assessor A	20	5.64	0.32	0.01*
5 kg assessor B	20	5.24	0.32	
6 kg assessor A	20	6.59	0.31	0.02*
6 kg assessor B	20	6.36	0.32	
7 kg assessor A	20	7.63	0.51	0.76
7 kg assessor B	20	7.67	0.36	

*Significant difference between the assessors ($P < 0.05$).

Discussion

To measure orthodontic bracket debonding force, electrical resistance strain gauges were adapted to Polypropylene 3M Unitek pliers. Strain gauges are defined as localized mechanical deformation sensors since all and any phenomenon responsible for mechanical deformation can be analysed. Therefore, strain gauges are transducers that convert mechanical displacement into a range of electrical resistance (Helfrick and Cooper, 1994). Because strain gauges take a measurement of deformation, five 2 mm diameter holes were made in the top one-third of the lateral active arm surface of the pliers with the aim of increasing the deformation resulting from manual application on this arm.

Table 4 Analysis of Adhesive Remnant Index and Kruskal–Wallis test.

	Score 0 (%)	Score 1 (%)	Score 2 (%)	Score 3 (%)	Mean rank	*P*
Group A	—	1 (4)	1 (4)	23 (92)	42.24	0.18
Group B	4 (16)	—	1 (4)	20 (80)	37.06	
Group C	2 (8)	3 (12)	2 (8)	18 (72)	34.70	

Group A, developed device.
Group B, tensile testing in a universal testing machine.
Group C, shear testing in a universal testing machine.

According to Borchardt and Zaro (1982), strain gauges are very sensitive and temperature alterations are able to influence the measurements. To compensate for any possible temperature alterations, the following procedures were adopted: (1) use of an electrical resistance strain gauge with temperature compensation for steel that self-compensates eventual temperature variations; (2) the gauges were bonded onto metal-coated surfaces composed of iron filings and cyanoacrylate to improve heat conduction and dissipate more heat; (3) the gauges were covered with silicone without acetic acid to prevent the influence of hand temperature; and (4) control of the laboratory mean temperature during the experiments.

Another important factor was to adequately join the strain gauge to the surface to which it would be bonded, so that deformation would be transmitted to the strain gauge without slipping (Helfrick and Cooper, 1994). To obtain a good bond, the metal-coated surface was cleaned with isopropyl alcohol and the two strain gauges were bonded with cyanoacrylate ester-based adhesive.

The strain gauges were bonded in the longitudinal direction of the plier handle. The strain gauge bonded to the anterior face of the handle was subjected to tension forces and that bonded to the posterior face to compression forces. When the pliers were used to debond the bracket, the strain gauge metal grid resistance generated a tension (millivolt) proportional to the deformation of the active arm of the pliers. The small amount of tension generated was multiplied by an amplifier circuit as sheet-type strain gauges require amplification due to the low output signal (Allocca and Stuart, 1984). Lastly, the amplifier generated a signal ready for kgf and displayed it in real time.

To gauge the device, weights from 1 to 7 kg were used. Although the mode of holding the pliers was standardized, there was a statistically significant difference in the values obtained between the assessors at 2, 3, 5, and 6 kg. This difference probably occurred due to the great sensitivity of the strain gauges, so that small changes in the way the pliers were held made a difference to the lever arm, and consequently, to the load mode. The values obtained also varied for the same assessor since the standard deviation increased as the weight increased. Although the device recorded grams above

the weight that was being used by both assessors, the results were considered to be satisfactory.

After the device had been gauged, orthodontic bracket debonding was performed *in vitro*. As the bracket debonding performed with a universal testing machine is not subject to operator variations, the values obtained with this method were compared with the device as a way of determining reliability. The tensile testing (group B) sought to reproduce the same conditions as debonding of the developed device. To do this, a hook was made of 0.40 mm diameter stainless steel wire, which reproduced the same thickness as the plier hook (group A). Furthermore, the hook made for the test machine was also placed on only one bracket wings at the time of the test, reproducing the same position used by the plier hook at the moment of debonding. Therefore, due to the fact that the hook did not embrace all the bracket wings, as in some studies (Wheeler and Ackerman, 1983; Siomka and Powers, 1985; Fajen *et al.*, 1990), the force was not uniformly applied to the bracket. In spite of calling this a tensile test, it is known that at the moment of bracket debonding, not only tensile forces occur but also an interaction of tensile, shear, and compressive forces (Thomas *et al.*, 1999).

In the universal testing machine, bracket removal was carried out under a constant crosshead speed of 0.5 mm/minute. According to Eliades and Brantley (2000), this load speed is generally used, although it does not correspond to clinical conditions since debonding *in vivo* occurs at a higher speed. Therefore, when using the pliers, a speed higher than 0.5 mm/minute was probably used for bracket removal. In spite of the differences among methodologies, the bond strength results did not differ statistically between the developed device (2.98 MPa) and tensile testing (2.69 MPa), which suggests that the device may be a useful tool for measuring bond strength *in vivo*. Furthermore, the standard deviation for both debonding procedures was low.

Shear testing was also performed with the intention of comparing the bond strength values with those of the other two methodologies. According to Millett and McCabe (1996), both shear and tensile force may be used for bracket debonding, but they recommend shear as it represents the clinical situation more closely, because the bracket bonded to the tooth is more subject to shear forces from masticatory action than tensile forces. The results of this study indicate that the debonding forces measured in the shear test mode were significantly higher than those with tensile testing. In shear testing, the bracket slides parallel of the substrate, while in tensile testing it is pulled perpendicular of the substrate (Powers *et al.*, 1997). According to Kitasako *et al.* (1995), one possible explanation for the different results between shear and tensile bond testing is that resin tags in the enamel would be less likely to resist forces perpendicular to the bonding surfaces *vis a vis* the tensile bond test. Such thinking can also be applied to brackets, where the surface has a mesh to bond mechanically to the composite resin. Therefore, bond strength values are dependent on the type of test used.

Orthodontic bracket bonding to teeth requires the bond system used to be sufficient to resist the forces present during the mechanics of orthodontics and mastication. Some authors suggest that values between 6 and 8 MPa are adequate for clinical situations (Reynolds, 1975; Meehan *et al.*, 1999; Bishara *et al.*, 2001). Nkenke *et al.* (1997), in a tensile test, concluded that bond strength values above 10 MPa are potentially dangerous as they may cause enamel fractures during bracket debonding. However, it is difficult to establish a numerical value since these values are dependent on several factors, such as the type of test used, the condition of the substrate (Schneider *et al.*, 1981; Kanemura *et al.*, 1999), the type of substrate (Nakamichi *et al.*, 1983; Oesterle *et al.*, 1998), whether or not thermal cycling is used (Jassem *et al.*, 1981), the geometry of the element to be tested (Van Noort *et al.*, 1989), the material involved (Egan *et al.*, 1996; Oesterle *et al.*, 2004), polymerization time (Evans *et al.*, 2002), the devices used in the test (Fowler *et al.*, 1992; Sinhoreti *et al.*, 2001), and the place where force is applied to the bracket (Katona and Moore, 1994; Klocke and Kahl-Nieke, 2005).

For this reason, various authors have emphasized the need for standardizing research methodologies to facilitate comparison of the results (Söderholm, 1991; Fox *et al.*, 1994; Stanford *et al.*, 1997). By virtue of the difficulty of comparing and extrapolating the results obtained in studies *in vitro* to the clinical situation, the minimum bond strength values required for safe clinical performance of orthodontic bonding procedures remain unknown.

ARI scores showed that in the three groups the fracture pattern was predominantly score 3, that is to say, the composite resin remained completely bonded to the enamel after debonding. Although there was no significant difference amongst the groups, shear testing resulted in the lowest percentage of score 3 (72 per cent), compared with debonding with pliers (92 per cent) and tensile testing (90 per cent). According to Olsen *et al.* (1997), score 3 is the one with the least probability of damaging the enamel, and according to Oliver (1988), the amount of composite resins remaining is dependent on the method used to debond the bracket. Therefore, debonding with the pliers was shown to be a safe method for preserving the enamel surface.

Conclusions

The developed device was shown to be feasible for measuring bracket debonding force *in vivo*.

Bond strength values were dependent on the method and direction of debonding. The values were higher for shear testing, while those for the device and tension tests in the universal testing machine were similar.

The method of debonding did not influence the ARI, and score 3 was predominant.

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