Original Article

Orthodontic In Vivo Bond Strength: Comparison with In Vitro Results

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Abstract: The purpose of the present study was to test a new in vivo debonding device and compare in vivo bond strengths recorded by this device with in vitro bond strengths recorded by a universal testing machine such as the Instron. For the in vitro part of the study, 60 extracted premolar teeth were divided into 2 groups of 30 each. Both groups of 30 teeth had 3M Unitek Victory Twin brackets, precoated with Transbond XT composite resin, bonded to them. Shear bond strength tests were carried out in vitro using the universal testing machine on one group of 30 teeth while the debonding device was used on the other group of 30 teeth. The mean shear bond strength of the group debonded using the universal machine was 11.02 MPa and that of the group debonded with the debonding device was 12.82 MPa. For the in vivo part of the study, 8 patients randomly assigned to the research clinician from patients in The University of Alabama School of Dentistry, Department of Orthodontics, had a total of 60 premolar teeth bonded with 3M Unitek Victory Twin brackets. Following comprehensive orthodontic treatment (average time of 23 months), shear bond strength tests were carried out using the debonding device, which can measure debonding forces in vivo. The mean shear bond strength recorded in vivo was 5.47 MPa. Statistically significant differences were found between all 3 groups tested. The results appear to indicate that mean bond strengths recorded in vivo following comprehensive orthodontic treatment are significantly lower than bond strengths recorded in vitro. (*Angle Orthod* 2001;71:141–148.)

Key Words: In vivo debonding device; Universal testing machine; Shear bond strength

INTRODUCTION

The direct bonding of orthodontic attachments has become a routine clinical procedure. Newman[1] introduced the concept of using epoxy resin and the acid etch technique to bond orthodontic attachments directly to teeth. Bonded orthodontic brackets have more advantages over bands in that they have no interproximal contact, are both easier to place and to remove, are more esthetic, hygienic and less irritating to the gingiva.[2] However, the use of composite resins as the bonding medium in orthodontics has disadvantages. Enamel can be lost during the debonding procedures as well as during the cleanup process of residual resin removal. This is of clinical significance since the concentration of fluoride is greatest at the surface of the enamel.[3]

The bond strength of adhesive and attachments should be sufficient to withstand the forces of mastication, the stresses exerted by the archwires, and patient abuse as well as allow for control of tooth movement in all 3 planes of space. At the same time, the bond strength should be at a level to allow for bracket debonding without causing damage to the enamel surface. Various studies have suggested bond strengths ranging from 2.8 MPa to 10 MPa as being adequate for clinical situations.[4–8] Retief[9] demonstrated enamel fractures on in vitro specimens with bond strengths as low as 9.7 MPa.

Bond strength tests have shown wide variation.[10] These studies are difficult to compare and interpret due to many variables such as the adhesives used, the substrate, and the design of the test. When a new bonding system is evaluated, its mean bond strength is compared with those values of bonding systems that have a clinical record of reliability. Optimum conditions for placement of brackets and moisture isolation exist only in the in vitro environment and, consequently, in vitro testing provides a guide to the selec-

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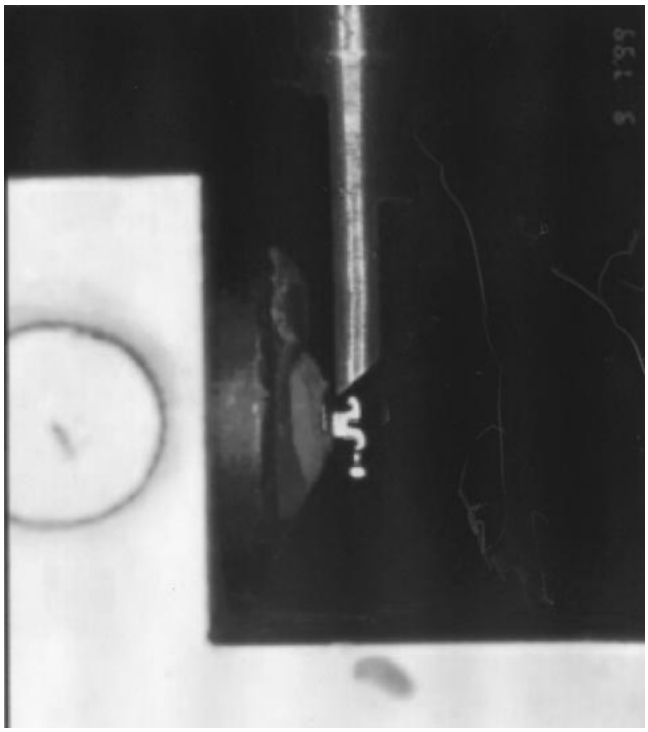

FIGURE 1. In vitro debonding using the Instron machine. Flattened-end steel rod of Instron machine applies occluso-gingival load to the bracket, producing a shear debonding force at the bracket-tooth interface.

tion of bracket/adhesive combinations.[11] It has always been assumed that the clinical test results would be similar to those in vitro.[12] However, for no apparent reasons, bonding systems with no statistically significant differences in the in vitro mean bond strength values appear to have different clinical failure rates.[13] On the other hand, it has been shown that different bonding systems with statistically significant differences between each other in mean bond strengths may have no statistically significant differences in clinical failure rates. It should be emphasized that no simple relationship exists between in vitro mean bond strength values and in vivo failure rates.

Ferreira[13] suggested the use of Weibull analysis as an approach to provide the clinician with more useful information relative to the extrapolation of in vitro data to clinical practice. The Weibull analysis allows for fracture probability to be calculated as a function of applied load or vice versa.[14] For example, in orthodontics, Weibull analysis would allow the researcher to calculate the in vitro probabilities of failure of a bonding system under loads encountered in the clinical situation or calculate the in vitro bond strengths based on failure rates obtained in the clinical situation. Weibull analysis may offer a better way of interpreting in vitro data; however, this is still a system that is based on predictions of bond strength values rather than on actual recordings of in vivo bond strength values. Hence, there is a need for a more accurate method of assessing in vivo bond strength values.

Considerable research has been conducted in evaluating the bond strength of various orthodontic bracket-bonding systems. Traditionally, orthodontic bonding systems have been evaluated by means of in vitro shear bond strength tests using a universal testing machine such as the Instron (Instron Corp, Canton, Mass). Even though the universal testing machine is considered the standard when it comes to assessing bond strength values, the results are, nevertheless, in vitro based. It would be preferable to record actual in vivo measurements to assess bond strengths since the bracket-bonding systems being tested are in environments that are different. To date, there are no validated devices designed to measure and record actual debonding forces in vivo. In a study by Martell-Ramos,[15] bond strengths were recorded for the first time in vivo using a newly developed debonding device that measures debonding forces in vivo. However, the debonding device requires validation since the recordings have not been compared or correlated with in vitro recordings.

The purpose of the present study was to test this new in vivo debonding device and compare in vivo bond strength recordings from this device with in vitro bond strengths recorded by the debonding device and the universal testing machine. The hypothesis is that in vivo bond strengths following comprehensive orthodontic treatment are lower than bond strengths recorded in vitro.

MATERIALS AND METHODS

In Vitro Study

Sample. The test sample consisted of 60 human premolar teeth that had been extracted for orthodontic purposes. The teeth were stored in a solution of 0.1% thymol at room temperature until the time of use (approximately 3 months). The criteria for tooth selection were an intact buccal segment with no cracks as a result of the pressure of the extraction forceps, no cement remnants as a result of previous orthodontic treatment, and no caries nor restorations.

Bonding procedure. The same clinician bonded all the teeth following the manufacturers' instructions. The enamel surface of the teeth were pumiced with nonfluoride-containing pumice and rinsed with copious amounts of water. They were dried with an oil-free, water-free air source, and the buccal surface of the teeth were etched with 37% phosphoric acid for 30 seconds and then rinsed for approximately 10 seconds with copious amounts of water. The teeth were dried with an oil-free, water-free air source, and a light coat of 3M Unitek primer-adhesive was applied to the enamel surface and light cured for 10 seconds.

Sixty 3M Unitek Victory Twin brackets, precoated with Transbond XT light-cured composite resin, were placed on the buccal surfaces of the teeth. Firm pressure was used to completely seat the bracket on the tooth, expelling excess

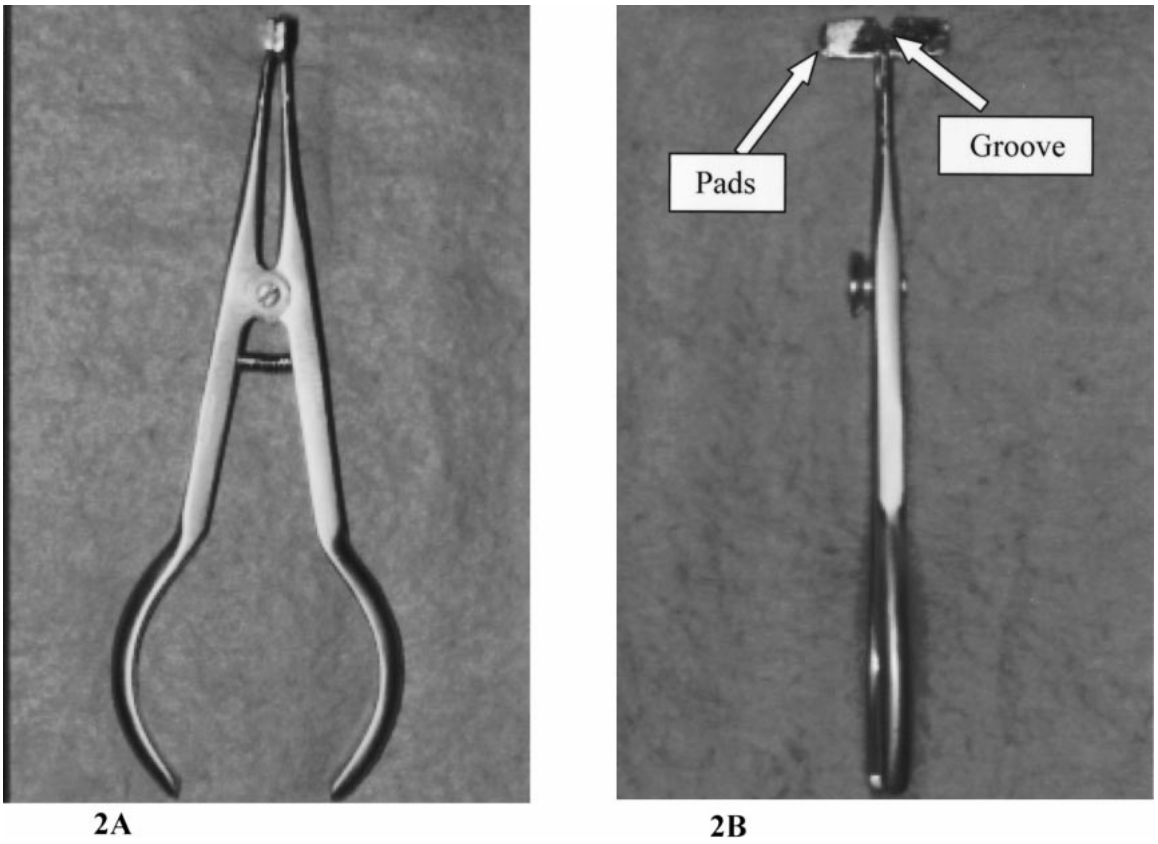

FIGURE 2. Debonding plier. The plier (A) consists of a modified elastic spacer placement instrument with soldered pads. A groove in the pads (B) allows the stainless steel cross-member to slide freely.

resin from around the bracket base. Any excess resin was removed from around the periphery of the brackets, with care taken not to disturb the bracket. Each bracket was light cured with an Ortholux™ XT visible light-curing unit (3M Unitek, 3M Dental Products Division, St Paul, Minn) for 40 seconds, 10 seconds per side of bracket.

Shear bond strength testing. The roots of the teeth were sectioned from the coronal portion of the tooth so that the coronal portion with the bracket could be mounted in brass cups with the facial surface projecting above the rim of the cup. The teeth were mounted in the brass cups using cold-cure orthodontic acrylic. The teeth were then divided into 2 groups of 30 each.

One group of 30 was debonded by securing each brass cup containing the specimen in a metal holding jig and then placing this apparatus on the compression load cell of a Model 1011 Universal Testing Machine (Instron Corp, Canton, Mass) set at a crosshead speed of 0.2 in/min. An occlusal-gingival load was applied to the bracket with a flattened-end steel rod attached to the crosshead of the universal testing machine (Figure 1). This produced a shear force at the bracket-tooth interface. The load at bracket failure was recorded electronically in pounds by a computer connected to the Instron machine. The shear bond strength values were calculated in MPa by dividing the force by the area of the bracket base.

The second group of 30 teeth was debonded using a debonding device able to measure debonding forces intraorally. The debonding instrument consisted of an elastic spacer placement instrument modified to produce the separation of two surfaces when compressed while allowing the stainless steel cross-member to move freely in a groove at pads soldered to the plier tips (Figure 2). The stainless steel cross-member consisted of a short arm that engaged the gingival portion of the bracket in a mesio-distal direction in the space between the bracket wings and base, while the longer perpendicular arm of the cross-member was soldered to a screw that attached to a digital force gauge (Mark-10 Model MG, Mark-10 Corp, Hicksville, N.Y.) (Figure 3).

For debonding, the brass cup containing the specimen was secured, as previously described, in the holding jig. One pad of the debonding plier tip rested against the metal jig while the other pad rested against a plastic cover on the digital gauge. This allowed for the cross-member, attached to the bracket base and digital gauge, to move away from the gauge. As the plier handles were slowly compressed, the plier tip pads moved away from each other, exerting force against the metal jig and plastic cover on the digital gauge. The gauge

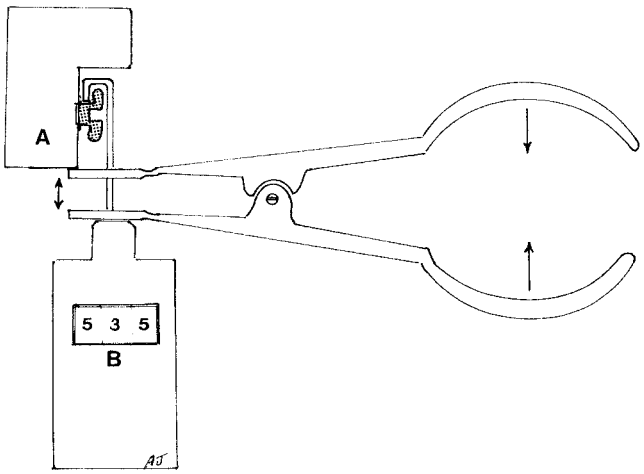

FIGURE 3. Diagrammatic illustration of in vitro debonding using the debonding device. As the plier handles are compressed, the tip pads move away from each other, exerting pressure against the metal jig (A) and plastic cover on the digital gauge (B). A shear debonding force is recorded as the cross-member moves away from the gauge and causes bond failure at the bracket-enamel interface. Note the reading of 5.35 lb displayed on the gauge.

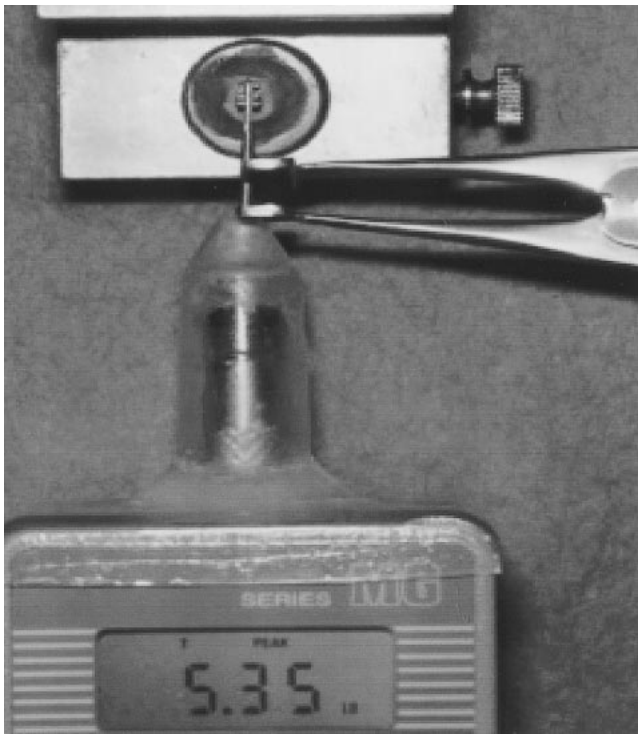

FIGURE 4. In vitro debonding using the debonding device.

recorded the debonding force through the cross-member engaging the bracket (Figure 4). At bracket bond failure, the gauge recorded a peak force. The cross-member was aligned to the long axis of each bracket base as much as possible to record shear forces. Debond forces were recorded in pounds and converted to MPa, as described previously.

In Vivo Study

Sample. The subjects participating in this clinical trial were randomly assigned to the clinician from the pool of patients seeking orthodontic treatment in the Orthodontic Department of the University of Alabama School of Dentistry. The inclusion criteria consisted of willingness to participate in this clinical trial through the signing of an informed consent form approved by the Institutional Review Board for Human Use of The University of Alabama at Birmingham. The informed consent contained a detailed explanation of the procedures involved in the study. The subjects included patients requiring extraction, nonextraction, and/or surgical procedures with class I, II, and III malocclusions. Exclusion criteria were based on the patient not wishing to participate in the study and not giving consent. In an attempt to mimic the population that would seek orthodontic treatment at any orthodontic office, the inclusion criteria did not eliminate any type of treatment procedure, malocclusion, race, or gender.

Bonding procedure. The same clinician bonded all teeth according to the manufacturers' instructions. The enamel surface preparation was the same as for the in vitro study, with the addition of maintaining appropriate tooth isolation intraorally. All patients were bonded with 3M Unitek Victory Twin brackets, precoated with Transbond XT light-cure composite resin, and light cured as described in the in vitro study.

The initial arch wires on all patients were 0.014-inch nitinol (ORMCO Corporation, Glendora, Calif), placed approximately 5 minutes after curing the last bracket. Elastic modules were used to retain the initial arch wires on all patients.

The prescribed orthodontic mechanotherapy was carried out on each individual patient. Arch wire size and shape were employed according to the dictates of the required orthodontic treatment.

Shear bond strength testing. The first 8 patients to complete their comprehensive orthodontic treatment were selected to participate in this clinical trial to study in vivo debonding forces. At the appointment before debonding, alginate impressions were taken of both the maxillary and mandibular arches. The stone models of each arch were used to make acrylic splints 2 mm in thickness that covered the occlusal surfaces of all the teeth without contacting the premolar brackets. The splints were designed to protect the teeth and distribute the occlusal debonding forces. In order to minimize the variables, only premolar brackets were debonded, as was done in the in vitro study.

For debonding, one pad of the debonding plier tip rested on the splint protecting the occlusal surfaces of the teeth and the other pad rested against a plastic cover on the digital gauge that allowed for the cross-member, attached to the bracket base and digital gauge, to move away from the gauge. As the plier was slowly compressed, the plier tip pads moved away from each other, exerting force against

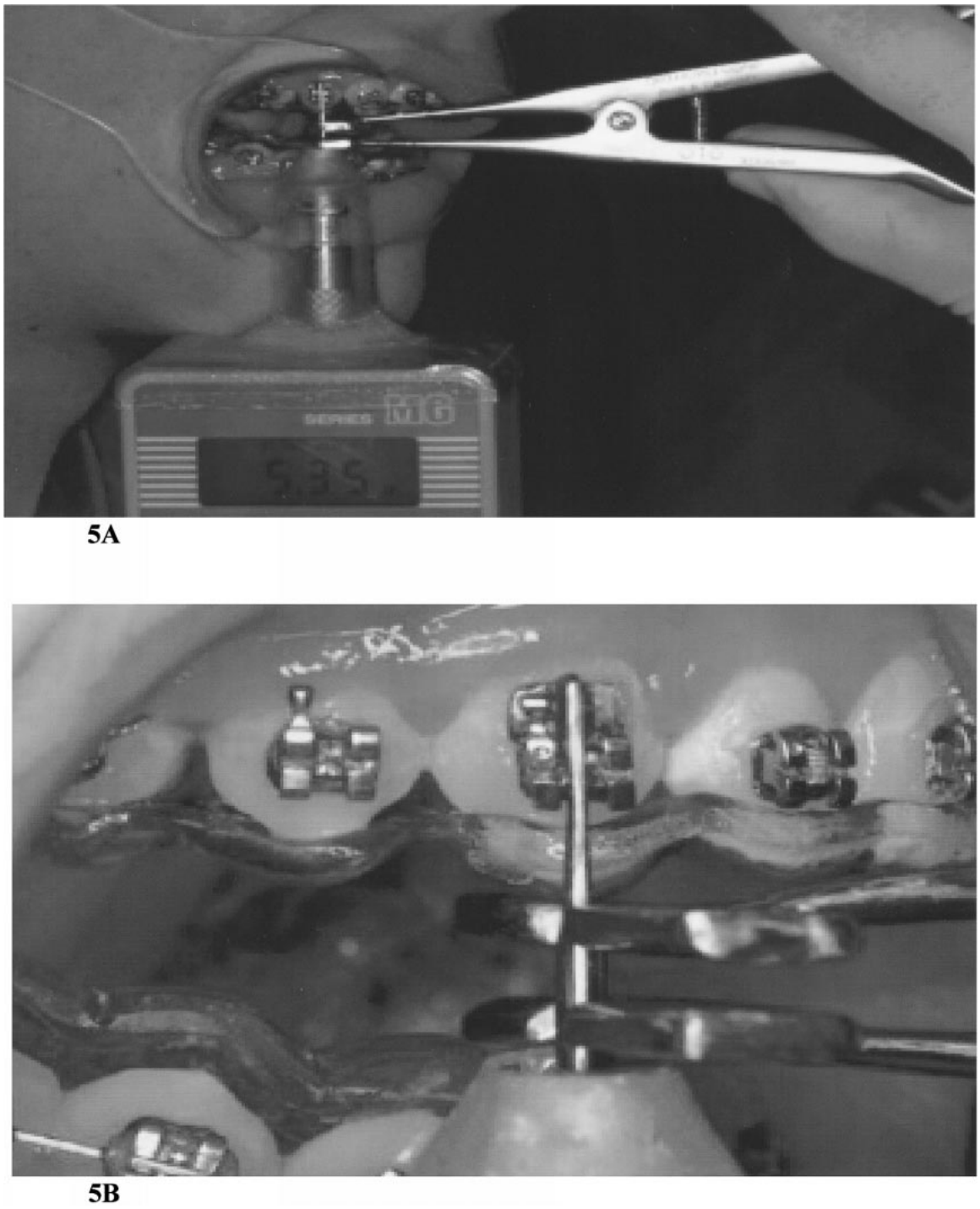

FIGURE 5. In vivo debonding using the debonding device. (A) Extraoral view. (B) Intraoral view. As the plier is compressed, the plier tip pads move away from each other, exerting pressure against the occlusal splint on one side and the plastic cover of the gauge on the other. A shear debonding force is recorded as the cross-member moves away from the gauge and causes bond failure at the bracket-tooth interface.

the occlusal splint on one side and the plastic cover of the digital gauge on the other side, while the gauge recorded debonding forces through the cross-member engaging the bracket (Figure 5). At bracket bond failure, the gauge recorded a peak force. The cross-member was aligned to the long axis of each bracket base as closely as possible to record shear forces. Debond forces were recorded in pounds and converted to MPa, as described previously.

Statistical Analysis

Descriptive statistical analysis was used to calculate means, standard deviations, and minimum and maximum

TABLE 1. Mean Bond Strength Values (MPa) for the 3 Debonding Methods

Debonding Method	Mean	SD	Minimum	Maximum
In vitro, universal testing machine (n = 30)	11.02	4.49	4.83	21.46
In vitro, debonding device (n = 30)	12.82	3.05	5.44	20.83
In vivo, debonding device (n = 60)	5.47	2.18	1.81	9.52

TABLE 2. Analysis of Variance (ANOVA) Results

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	*F*-value	Significance Level
Between groups	1297.21	2	648.65		
Within groups	1136.67	117	9.72	66.77	0.0001

values. The comparison of sample means was carried out using a one-way analysis of variance (ANOVA). The ANOVA compares the within-group variance with the between-groups variance. A post hoc test was used to determine which, if any, of the means were significantly different from the others. The post hoc test reveals how far apart 2 means have to be before they have a statistically significant difference at a chosen confidence level.

RESULTS

Eight patients were included in the in vivo part of the study. The period of orthodontic treatment for these 8 patients ranged from 19 to 27 months, with a mean treatment time of 23 months. A total of 60 premolar brackets were debonded using the intraoral debonding device, which measured debonding forces in vivo. None of the 60 premolar brackets had been rebonded at any time during treatment.

The mean shear bond strength and standard deviations for each debonding method tested are shown in Table 1 and in Figure 6. The maximum and minimum values for each group are also shown. It can be seen that in vitro debonding using the intraoral debonding device produced the highest mean bond strength, 12.82 MPa. In vitro debonding using the universal testing machine produced the next highest mean bond strength, 11.02 MPa. In vivo debonding using the intraoral debonding device produced the lowest mean bond strength, 5.47 MPa.

Table 2 shows the results of the ANOVA. Table 3 shows the comparison of mean bond strengths for the 3 materials using the post hoc test. There was a statistically significant difference ($P \leq .05$) between all 3 materials with respect to bond strength.

TABLE 3. Statistical Comparison of Mean Bond Strengths Using Post Hoc Test

Means Compared[a]	Difference Between Means (MPa)	Significance Level
In vitro UTM and in vitro DD	1.80	0.0271
In vitro UTM and in vivo DD	5.55	0.0001
In vitro UTM and in vivo DD	7.35	0.0001

[a] UTM, universal testing machine; DD, debonding device.

DISCUSSION

The results of this study indicated that debonding forces measured in vivo were significantly lower ($P = .0001$) than those measured in vitro, which supports the hypothesis that in vivo bond strengths following routine orthodontic treatment are lower than in vitro bond strengths.

The universal testing machine served as the gold standard with which to compare the results obtained from the debonding device. The mean bond strengths recorded using the debonding device in vitro (12.82 MPa) were slightly higher than the in vitro bond strengths recorded using the universal testing machine (11.02 MPa). Although the difference between the means of the 2 in vitro tests was numerically small (1.80 MPa), this was a statistically significant difference ($P = .0271$). This difference in mean in vitro bond strengths was expected since the testing systems used were different. The universal testing machine is a stable and rigid device capable of producing pure shear debonding forces, whereas the debonding device may be introducing a combination of debonding forces, eg, shear, peel, and tensile forces. In addition, the rate of loading for the universal testing machine is constant, whereas the rate of loading for the debonding device is not standardized or constant due to its clinical application. However, the similarity between the mean bond strength recorded using the debonding device in vitro and the mean bond strength recorded using the universal testing machine suggests that the debonding device may be a useful tool for measuring bond strengths in vivo.

It could be noted that the standard deviations for both in vitro tests were high (universal testing machine, ± 4.49; debonding device, ± 3.05). The high standard deviations possibly could be attributed to variations in the biological tissue examined, eg, differences in etching patterns of teeth, depth of etch, fluoride concentrations, and irregularities in the surface enamel. Variations in operator technique and the bonding materials used could also have contributed to the high standard deviations obtained.

When comparing the in vitro and in vivo results using the intraoral debonding device, the bond strengths recorded in vivo following orthodontic treatment were significantly lower ($P = .0001$) than the bond strengths recorded in vitro. Possible reasons for the lower bond strengths recorded

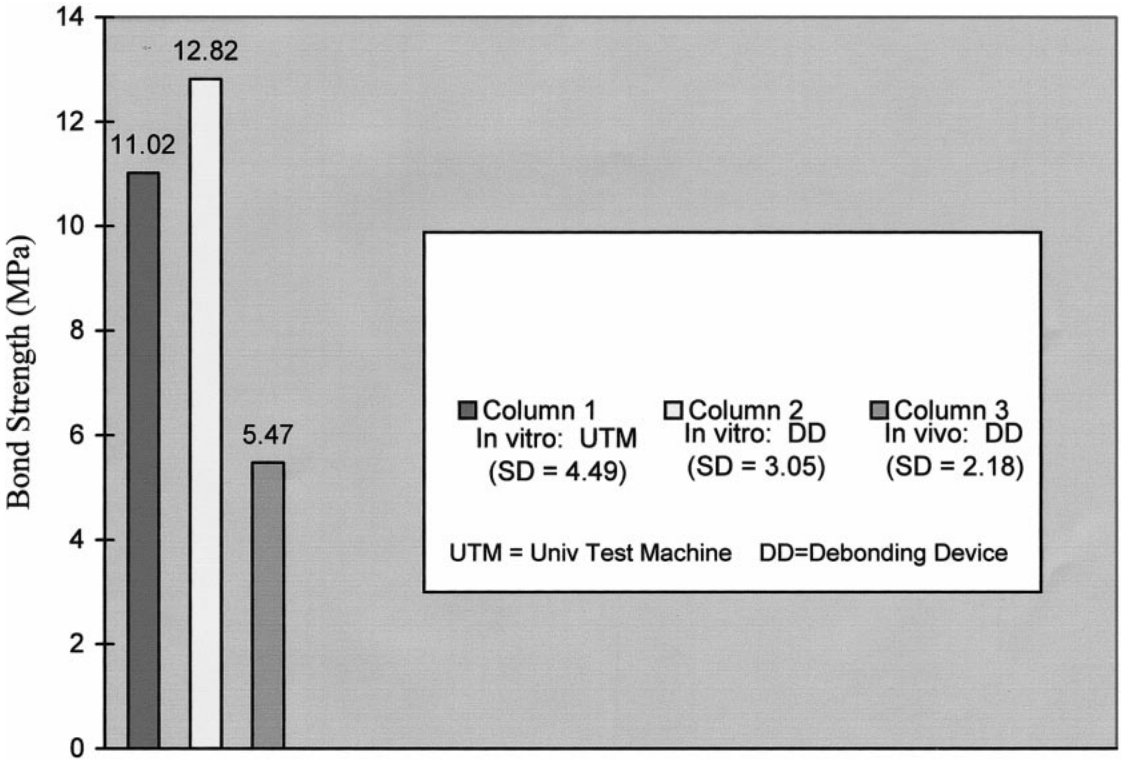

FIGURE 6. Bar graph illustrating the differences in mean bond strengths between the 3 groups.

in vivo could be the length of time the appliance was in the oral environment, exposing the bonded brackets to acid, saliva, patient abuse, and masticatory forces, all of which may have contributed to the decreased bond strength.

Bonding orthodontic brackets to teeth requires that the bonding system used be able to resist the forces present during orthodontic mechanotherapy and mastication. However, excessively high bond strength values are undesirable because of the increased debonding forces needed, resulting in possible damage to enamel. Retief [9] demonstrated in vitro enamel fractures on specimens with bond strengths as low as 9.7 MPa. The latter bond strength value is comparable to the mean linear tensile strength of enamel. Hence, it may be prudent to suggest a bond strength of less than 9.7 MPa. According to Newman,[16] the orthodontic force applied to brackets during treatment is approximately 1 MPa, with a maximum of approximately 3 MPa probably occurring under certain clinical conditions. Numerous studies[17–21] have suggested bond strengths ranging from 2.8 MPa to 10 MPa as being adequate for clinical situations. The bond strength values recorded in the present study are within the range of values that have been suggested by other researchers as being essential for clinical success.

The minimum in vitro bond strength required for clinical reliability of orthodontic bonding procedures is still unknown and will vary, depending on such factors as the adhesive system used, bracket base design, enamel morphology, appliance force systems, and clinician's technique.[22]

It has been traditional to extrapolate in vitro data to in vivo situations as they relate to the testing of orthodontic bond strengths. However, considerable controversy exists regarding the reliability of comparing the data from in vitro bond strength studies with those of a clinical environment. In a study by Ferreira,[13] Weibull analysis was used in an attempt to minimize the empiricism when extrapolating the results from laboratory tests to clinical practice. Weibull analysis allows for fracture probability to be calculated as a function of applied load or vice versa.[14] For example, in the study by Ferreira,[13] an overall failure rate of 6% was recorded for the bonding systems being tested. The 6% failure rate was used in the Weibull analysis to predict the minimum in vitro bond strength required for acceptable clinical performance of orthodontic bonding systems, and this probability of failure was found to correspond to an in vitro bond strength of 3.4 MPa. The minimum in vitro bond strength (3.4 MPa) calculated was obtained from bonding materials that yielded in vitro mean bond strength values of 9.4 MPa and 8.8 MPa. This emphasizes the inappropriateness of extrapolating the results from laboratory tests to clinical practice by relating in vitro bond strength values to in vivo failure rates.

Although the Weibull analysis offered a better method of dealing with in vitro data, it remains a system based on predictions of bond strength values rather than actual recordings of in vivo measurements. The intraoral debonding device tested in the present study is considered to be of

greater value in determining the actual bond strengths in vivo following comprehensive orthodontic treatment. It is considered that the results reported in the present study provide a more accurate account of actual in vivo bond strengths when compared with other studies that rely on in vitro results to assess bond strengths required for clinical success. These findings may be of assistance to bracket and adhesive manufacturers by enabling them to develop products based on actual in vivo bond strengths. This, in effect, could help maximize clinical success and, at the same time, minimize the risk of enamel fracture during debonding.

CONCLUSIONS

A new method of recording forces while debonding orthodontic brackets in vivo was tested in the present study. The results indicated that the mean bond strength recorded in vivo following comprehensive orthodontic treatment was significantly lower than the bond strength recorded in vitro. This confirmed the initial study hypothesis that in vivo bond strengths are lower than those recorded in vitro. In vivo, the bonding systems are exposed to numerous intraoral factors including saliva, acid, masticatory forces, variable patient abuse, and orthodontic mechanotherapy during the time period of comprehensive orthodontic treatment. In vitro, on the other hand, the bonding systems tested are not exposed to the in vivo environment nor is there the tooth isolation factor during the bonding procedure.

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