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An *Ex Vivo* Study to Investigate Bond Strengths of Different Tooth Types

ROGNVALD A. LINKLATER, B.M.SC., B.D.S., F.D.S.R.C.S.ENG., M.SC., M.ORTH.R.C.S.(ED.)
Orthodontic Department, Middlesbrough General Hospital, Ayresome Green Lane, Middlesbrough, TS5 5AZ, UK

PETER H. GORDON, PH.D., B.D.S., F.D.S.R.C.S.ENG., M.ORTH.R.C.S.(ENG.)
Department of Child Dental Health, Newcastle Dental School, Framlington Place, Newcastle upon Tyne, NE2 4BW, UK

Abstract *This study aimed to identify the presence and pattern of differences in* ex vivo *shear bond strength between tooth types when bonding orthodontic brackets using Right-On®, and took the form of a prospective laboratory study of bond strength on different tooth types, at the Newcastle University Dental School Materials Science Laboratory, 1997–1999.*

Ex vivo *bond strength testing was undertaken using the technique described by Fox* et al. *(*BJO *18, 125–130, 1991) on a total of 120 extracted incisor, canine, and premolar teeth of each dental arch. Analysis was by one-way ANOVA with Tukey's pairwise comparisons, and by Weibull Analysis. Shear stress to failure (measured in MPa) was recorded on Instron® 5567 universal testing machine.*

Significant differences in mean bond strength existed between different tooth-type series. Canine (upper 12·3, lower 12·1) and premolar (upper 11·9, lower 10·9) teeth exhibited higher strengths than incisors (upper 6·9, lower 9·0).

The results of this study confirm that ex vivo bond strength is not uniform across all teeth.

Index words: Orthodontic Bonding, Shear Bond Strength.

Introduction

The materials involved in orthodontic bonding have been a field of constant change since the acid etch technique (Buonocore, 1955) permitted adhesion of acrylic filling materials to enamel surfaces. New bonding materials are tested to ascertain whether they represent an improvement on those previously used. The ideal system would be quick and easy to place, remain *in situ* with sufficient bond strength to resist dislodging forces during the active treatment period, and be debonded at the end of treatment without complication. A number of means of assessing the success of a bond are available, including measurement of bond strength *ex vivo* or the recording of bond failure *in vivo*. The simplest of these is *ex vivo* bond strength testing.

Recording of bond strength can be achieved with a considerable degree of accuracy using modern testing systems and enables comparison of new materials with other materials already in use at the time of testing. The use of a universal-testing machine (e.g. Instron®; Zwick®) in orthodontic bond strength testing is widespread. These machines are capable of delivering a controlled and measured force to the bonded bracket via a moving crosshead (Figure 1). International Standards Organization (ISO, 1991) suggest testing to failure in shear, with the values of stress quoted in mega pascals (MPa).

Fox *et al*. (1994) outlined the difficulties encountered in interpreting data published in support of bond strength claims due to a lack of standardization in the methodology. Comparison of results without standardization is of limited value. A number of suggestions arose from this critique in order to eliminate variables that were not under direct examination. These included recommendations about the nature of the storage media, the testing equipment, minimum sample sizes and the reporting of test findings.

Since Newman (1965) first reported *ex vivo* bond strengths of epoxy adhesives in orthodontics, there has been a consistent tendency for research workers to report increased *ex vivo* bond strengths of new materials as indicating improved clinical performance. The validity of the long-held assumption that a high *ex vivo* bond strength is synonymous with low failure rates or enhanced clinical survival has been questioned. Sunna and Rock (1998) cast doubt over the applicability of this assumption when comparing *ex vivo* bond strength with *in vivo* clinical bond failure rates. Significant differences in *ex vivo* bond strength between various bracket/adhesive combinations did not correlate with clinical failure rates, which demonstrated no significant differences.

Extracted premolar teeth have formed the basis of most bond strength tests to date (Fox *et al*., 1994), possibly due to the relative ease of obtaining test specimens following orthodontic extractions. Results obtained from premolar testing have been interpreted as being applicable to all teeth in both dental arches. The validity of this interpretation has, however, not been proven. To date, only one study has examined whether premolar bond strengths are representative of all tooth types. Hobson *et al*. (1999) examined variations in shear bond strength between different tooth types. Their findings suggest that significant differences in shear bond strength exist between different tooth types and opposing dental arches. Upper anterior teeth demonstrated higher shear bond strengths than upper posterior teeth and lower posterior teeth demonstrated higher shear bond strengths than lower anterior teeth.

Recent evidence has suggested that different tooth types exhibit biological variation in their etch pattern after acid priming (Hobson and Mattick, 1997, 1998; Mattick and Hobson, 2000) and it has been proposed that these differences between tooth types may influence the bond strength

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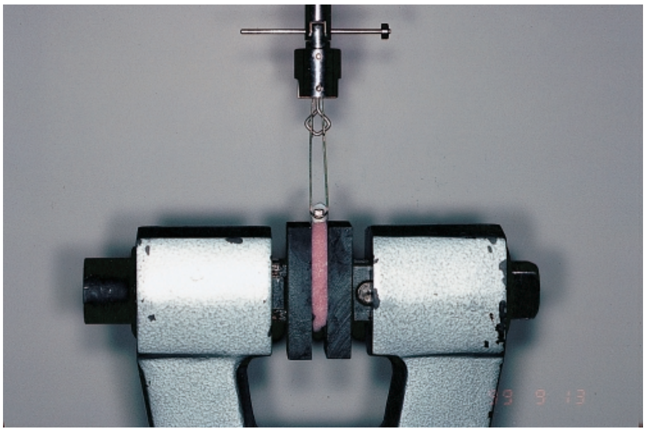

FIG. 1 Specimen undergoing shear bond strength testing to failure on Instron® 5567 universal testing machine.

that is achieved. This study set out to explore certain shortcomings in the current knowledge of orthodontic bonding. The following aims have been addressed:

1. To confirm whether significant differences in shear bond strength exist between different tooth types *ex vivo*.
2. To identify what the pattern of *ex vivo* bond strength is between different tooth types when bonding with Right-On, a no-mix composite orthodontic bonding adhesive.
3. To compare the findings of this study with a previous study of bond strength using the same methodology, but different bonding materials, to confirm whether significant differences in the pattern of bond strength exist between differing orthodontic adhesives.

Materials and Methods

One-hundred-and-twenty healthy human teeth extracted within the Oral and Maxillofacial Surgery Department of Middlesbrough General Hospital and peripheral units were collected over a 6-month period, and stored immediately after removal and continuously until testing in a solution of 0·5 per cent chloramine T disinfectant at room temperature. The teeth collected included all tooth types with the exception of molars (i.e. incisor, canine, premolar) from both dental arches.

The teeth were sorted into six groups (A to F) according to tooth type:

A Upper incisors
B Upper canines
C Upper premolars
D Lower incisors
E Lower canines
F Lower premolars

Once sorted, the teeth were subjected to root surface notching using a steel bur in a slow speed dental handpiece, then embedded individually in slabs of Betacryl II® (Procare Dental, Carr House, Carrbottom Road, Bradford, UK) denture base acrylic such that the roots were fully embedded in acrylic with the crowns exposed (Figure 2). The orientation of the teeth in acrylic was such that the tangent to LA (Andrews, 1976) point lay perpendicular to the plane of the slab. This was undertaken in an effort to minimize peel and maximize shear during testing. Each tooth was ascribed a number prefixed by the letter relating to which tooth type it was (e.g. A8). These numbers were inscribed onto each acrylic slab using a steel bur in a slow speed dental handpiece.

Once numbered, each tooth was identified for specific tooth type (e.g. upper right lateral incisor) to ensure that the correct bracket corresponding to that specific tooth type was bonded. Each tooth type group (A–F) comprised 20 teeth except Group E ($n = 10$) and Group F ($n = 30$). One-hundred-and-twenty Ovation® (GAC International, Inc., Central Islip, NY, USA) Roth prescription 0·022-inch slot brackets were used appropriate to each specific tooth type. The bracket bases were mesh-backed and contoured.

Measurement of projected base surface area for each bracket type was performed using an Optomax Image Analyser® (Micro Measurements Ltd, Shire Hill, Saffron Walden, Essex, UK). This recorded the area of five brackets of each type on five successive occasions to derive a mean surface area per bracket, thereby allowing approximate conversion of force values into stress values (Newtons into mega pascals). The image analyser provided nominal cross-sectional areas of the bracket bases, but was unable to account for the curvature of the bracket base, nor for the increase in base surface area due to the mesh backing. The conversion into stress values is therefore a best estimate. True determination of bracket base area taking account of these additional factors was not possible. These errors existed to a similar degree for all brackets, so it was considered reasonable to use these measurements to compare brackets with each other.

The teeth were bonded and tested in batches corresponding to their tooth type. The protocol for testing the effect of different tooth types on bond strength was similar to that described by Hobson *et al.* (1999). Tooth preparation involved prophylaxis using pumice/water slurry for 15 seconds then rinsing under tap water. Buccal surface enamel was etched using 36 per cent phosphoric acid gel (DeTrey Conditioner 36®, Dentsply De Trey, D-78467 Konstanz, Germany) for 30 seconds then rinsed with water for 15 seconds and a water/air mixture for a further 15 seconds prior to air drying using oil-free compressed air until frosted. All attachments were bonded using Right-On®. The etched

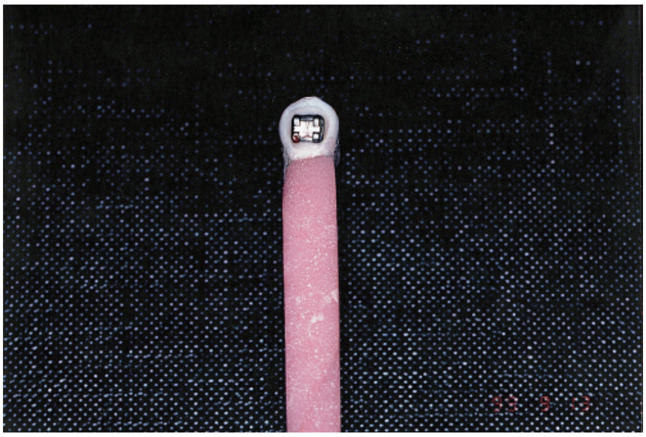

FIG. 2 Tooth embedded in acrylic with bracket bonded to buccal surface, prior to testing.

tooth surface and the bracket base had Right-On® liquid primer applied to them. Right-On® adhesive paste was then applied to the bracket base prior to seating on the tooth surface. All brackets were positioned on LA point (Andrews, 1976). Brackets were pressed against the tooth surface in their final position to ensure good approximation of constituents and to express excess adhesive. Peri-bracket flash was removed with a probe.

Once bonded, the teeth were stored in distilled water at 37°C (Raven Oven®, LTE Scientific, Greenfield, Oldham, UK) in darkness for 24 hours prior to testing. Bond strength testing was undertaken using the technique described by Fox *et al.* (1991). Orthodontic bond strength may be tested either in tension or shear, although Fox *et al.* (1994) suggested that control of the force vector can be difficult and resolution of the forces may reveal the force to be neither purely tensile nor purely in shear. They suggested use of a universal joint and a wire loop engaging the tie-wing slot fully in order to reduce directional error and enhance standardization. Shear bond strength to failure was tested on an Instron® 5567 Universal Testing Machine (Instron Corporation, 100 Royall Street, Canton, Mass. 02021, USA) with a crosshead speed of 1·0 mm per minute and a wire loop engaging the gingival tie-wings (Figure 1). Specimens were mounted on a universal joint to ensure the direction of shear loading was gingivo-occlusal.

The laboratory bond strength data was subjected to one-way analysis of variance (ANOVA) and Weibull analyses. The ANOVA provided group means with 95 per cent confidence intervals to enable comparison of within group variance and between group variance. Tukey's pairwise comparisons were undertaken in preference to multiple *t*-tests as a means of determining which group means were significantly different from which others. This was done in order to reduce the multiplication of type one errors (false positives) that can be generated by multiple *t*-tests (Bulman and Osbourne, 1989).

The Weibull analysis (Weibull, 1951) was applied to generate probabilities of failure at given levels of stress for each tooth type. The Weibull data allowed generation of characteristic stresses at which 5 and 10 per cent of brackets would fail for each tooth type tested, together with their 95 per cent confidence intervals. Lack of overlap of these 95 per cent confidence intervals enabled a quick assessment of whether two groups were significantly different.

Results

Table 1 illustrates descriptive statistics of the bond strength characteristics relating to the six groups of teeth (A–F) sorted by tooth type. The mean bond strengths in mega pascals for brackets bonded to each tooth type are presented together with the median values for each group, the group ranges, standard deviations, and standard errors of the mean.

Considerable variation was evident between the means for each group. In both dental arches brackets bonded to incisor teeth achieved the lowest mean shear bond strengths and those bonded to canine teeth achieved the highest strengths. Upper incisors achieved the lowest mean shear bond strength (6·95 MPa) of the sample and upper canines the highest (12·27 MPa). A boxplot of the distributions of stress to failure illustrating the means for each group and the 25 per cent quartiles is presented in Figure 3.

The summary statistics from the one-way analysis of variance are presented in Table 2.

The one-way ANOVA identified the presence of statistically significant differences within the data sample. Tukey's pairwise comparisons identified between which group means these significant differences had occurred. These

TABLE 1 *Descriptive statistics from* ex vivo *shear bond strength testing by tooth type*

Variable	*n*	Mean	Median	SD	SE mean
Series A	20	6·95	6·31	2·85	0·64
Series B	20	12·27	12·20	2·52	0·56
Series C	16	11·87	12·05	2·24	0·56
Series D	18	8·95	9·32	1·63	0·38
Series E	8	12·07	13·30	2·78	0·98
Series F	26	10·94	10·95	2·33	0·46

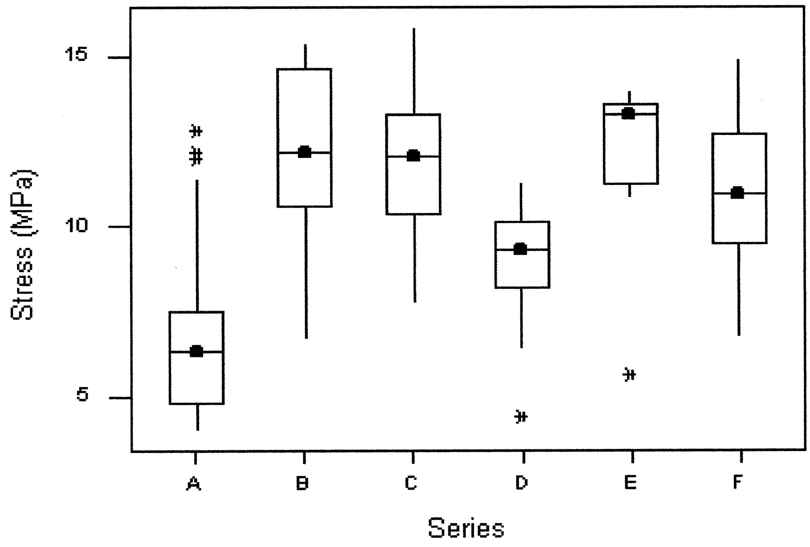

FIG. 3 Box plot of failure stress distribution for each tooth type.

differences are illustrated in Table 3. Significant differences between groups are identified by examining the values at the intersection of groups within the grid in Table 3. If the two values at a given intersection span zero, it is valid to conclude that there is not a significant difference between the means of the two groups under examination.

Group A (upper incisors) demonstrated significant differences from groups B (upper canines), C (upper premolars), E (lower canines), and F (lower premolars). Group D (lower incisors) demonstrated significant differences from groups B (upper canines), C (upper premolars), and E (lower canines). There were no other significant differences between the means for any other groups of tooth type.

Weibull analysis was undertaken on the *ex vivo* bond strength data. This generated probabilities of failure at given levels of applied stress (Weibull, 1951; McCabe and Carrick, 1986) for each tooth type. It was thus possible to generate the characteristic stresses associated with failure in 5 and 10 per cent of brackets for each tooth type, as these are levels of failure deemed to be clinically acceptable. These stresses and their 95 per cent confidence intervals are presented in Tables 4 and 5, together with the Weibull modulus for each tooth type.

Higher Weibull moduli indicate closer grouping of bond strengths. The highest Weibull modulus was noted for lower incisors (7·50), suggesting that even though the mean bond strength was low, the stress required for bond failure was highly predictable. Upper incisors conversely demonstrated the lowest Weibull modulus within this sample (2·65), suggesting that the stress required for bond failure was unpredictable in addition to being low in magnitude. The data from the Weibull analysis is presented graphically in Figures 4 and 5. The graphs given for each dental arch plot the cumulative probability of bond failure within any tooth type against applied stress.

The Weibull curve for upper incisors is clearly distinct from that of other teeth. This finding corresponds with the marked difference between the Weibull modulus of upper incisors and those of the other tooth types. It is possible to

TABLE 2 One-Way Analysis of Variance *for stress*

Source	DF	SS	MS	*F*	*P*
Series	5	411·29	82·26	14·34	0·000
Error	102	585·16	5·74		
Total	107	996·45			

TABLE 3 *Tukey's pairwise comparisons*

Group	Intervals for (column level mean) – (row level mean)				
	A	B	C	D	E
B	–7·529 –3·126				
C	–7·263 –2·593	–1·935 2·734			
D	–4·265 0·258	1·063 5·586	0·533 5·316		
E	–8·045 –2·221	–2·717 3·107	–3·219 2·809	–6·087 –0·171	
F	–6·068 –1·928	–0·741 3·400	–1·282 3·142	–4·129 0·140	–1·680 3·949

Family error rate = 0·0500; Critical value = 4·11; Individual error rate = 0·00450.

TABLE 4 *Stresses associated with 5 per cent levels of failure*

Group	Stress (MPa)	95% CI lower limit	95% CI upper limit	Weibull modulus
A	2·56	1·63	4·01	2·65
B	8·27	6·74	10·14	6·32
C	7·88	6·29	9·86	6·15
D	6·43	5·38	7·69	7·50
E	8·68	6·47	11·65	7·41
F	6·88	5·63	8·41	5·45

TABLE 5 *Stresses associated with 10 per cent levels of failure*

Group	Stress (MPa)	95% CI lower limit	95% CI upper limit	Weibull modulus
A	3·35	2·31	4·86	2·65
B	9·27	7·85	10·94	6·32
C	8·86	7·37	10·65	6·15
D	7·08	6·12	8·19	7·50
E	9·57	7·56	12·11	7·41
F	7·85	6·66	9·25	5·45

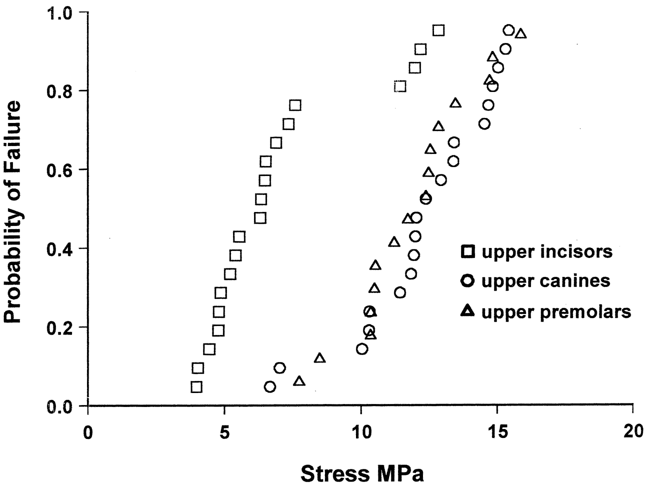

FIG. 4 Weibull graphs for maxillary arch.

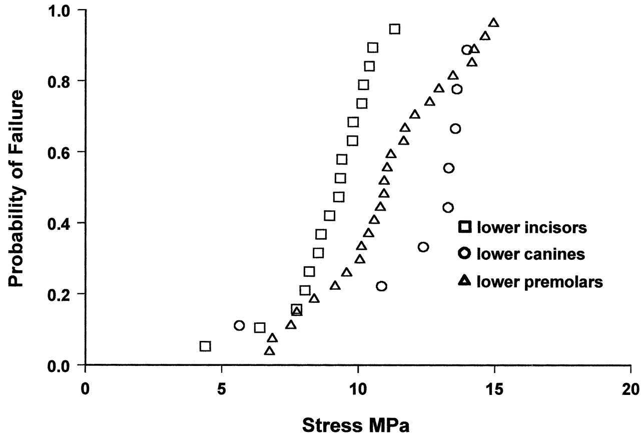

FIG. 5 Weibull graphs for mandibular arch.

obtain from these curves an estimate of the probability of bond failure at any given stress.

Discussion

Human teeth were used in this study in order to replicate as far as possible the *in vivo* clinical situation of bond failure. The teeth were extracted over a 6-month period, with their storage from extraction to testing being in 0·5 per cent chloramine T solution at room temperature. This differed from certain studies in which storage was either in chloramine refrigerated at 5°C (Hobson *et al.*, 1999) or in distilled water refrigerated at 5°C (Larmour *et al.*, 1998a; 1998b). The origin of the teeth was non-specific; previous studies have reported exclusive use of teeth removed for orthodontic purposes or of teeth from patients of a specific age range (Sunna and Rock, 1998; Larmour *et al.*, 1998a,b; Hobson *et al.*, 1999). It was necessary to be less specific about the origin of the teeth in this study in order to obtain sufficient numbers of teeth to provide adequate sample sizes for each tooth type, which McCabe and Walls (1986) and Fox *et al.* (1994) suggest as being no fewer than 20 teeth. Even so, it was not possible to obtain sufficient numbers of extracted lower canine teeth to match that sample to the others.

It is important to exercise caution in interpreting results if the origin of the teeth used is not fully known. Incisors are seldom removed for orthodontic purposes, so it would seem likely that those used in this *ex vivo* study came from a population of patients older than that typically undergoing orthodontic treatment. The enamel on these teeth may therefore have been qualitatively different from that present in orthodontic patients *in vivo*, with a higher surface fluoride content (Weatherell *et al.*, 1972). This feature may be responsible for the significant differences in bond strength recorded between incisors and other tooth types.

Testing was performed in a widely accepted manner (Fox *et al.*, 1991). Testing at 24 hours was chosen as it has been widely reported previously, and permitted comparison with other *ex vivo* bond strength studies. The predominant vector of force was in shear. This was achieved by means of careful embedding and bracket bonding together with use of a wire ligature to engage the bracket tie-wings fully. Jigs were not used to standardise mounting and testing, and this may have contributed to the relatively wide spread of data within each study sample (Littlewood and Redhead, 1998). The direction of shear force was gingivo-occlusal. This differs from that used in certain studies (Sunna and Rock, 1998) and it is unlikely that this mimics the loading a bracket receives during mastication. Comparison of results between this study and other *ex vivo* studies with a different direction of debond force may reveal differences purely related to the force direction. In addition, the fact that the *ex vivo* testing was performed in a manner dissimilar to *in vivo* loading may limit the value of comparisons made between the two.

The results of this study suggest that shear bond strength of orthodontic brackets varies between tooth types. This finding supports the work of Hobson *et al.* (1999) in which tooth type was found to have a significant effect on the bond strength achieved with Transbond®. The patterns of bond strength recorded in this study differed from those recorded by Hobson *et al.* (1999). In this study upper incisors demonstrated significantly lower mean shear bond strength than all other tooth types except lower incisors, whereas Hobson *et al.* (1999) found upper incisors to obtain the highest shear bond strength of all teeth. Lower canines in this study demonstrated significantly higher mean shear bond strength than lower incisors, whereas Hobson *et al.* (1999) found no statistical difference between these tooth types.

The protocol for tooth preparation, subsequent storage and testing in this study matched that used by Hobson *et al.* (1999). The most significant differences in technique were the use of a different adhesive and of slightly different brackets. Base surface areas between the two types of brackets were closely matched (<10 per cent), and always above the 6·82 mm^2 threshold found to be critical by MacColl *et al.* (1998). The role played by non-identical brackets in generating differences should therefore be minimal.

The origin of every tooth in the study by Hobson *et al.* (1999) was recorded as being from patients aged 10–22 years of age living in NE England. Although the teeth in this study were similar in that they were from the same broad geographical location, it was not possible to be specific in ascribing an age range to the patients from whom the teeth had been extracted. It is possible that this may have led to the differences in bond strength pattern by tooth type, particularly that which affected incisors in this study.

The other variable between this study and Hobson *et al.* likely to have contributed to the different bond strength patterns was the type of adhesive used. It is known that the light-cured composite adhesive Transbond® behaves differently to the no-mix chemically cured composite adhesive Right-On®. Although Wang and Meng (1992) found light-cured composite bond strengths at least matched those of chemically cured composites and Sargison *et al.* (1995) found no difference in shear bond strength between Transbond® and Right-On®, the profile by which the final bond strength is attained for each material differs. Chamda and Stein (1996) found that both set materials increased in bond strength over the first 24 hours, but the chemically-cured composites started at a strength below that deemed to be clinically adequate whereas light cured composites stared with strength above that threshold. Sunna and Rock (1999), however, did find a significantly higher shear bond strength with Transbond® than with Right-On® in tests on premolars *ex vivo*. This finding is not borne out when premolar bond strengths are compared between this study and those obtained by Hobson *et al.* (1999) using Transbond®. In their study, mean upper premolar bond strength (9·2 MPa) was less than in this study (11·9 MPa) and their mean lower premolar bond strength (8·9 MPa) was also less than in this study (10·9 MPa).

Right-On® is dependent upon adequate integration of its two phases to ensure full polymerization. If incomplete polymerization occurs, the potential exists for the resulting bond to be weak and prone to cohesive failure. Similarly, Transbond® may also polymerize incompletely if not exposed to sufficient light beneath the bracket base. This may also adversely affect bond performance. Both materials, although manipulated differently, are therefore technique sensitive.

Survival of both materials was found by Armas Galindo *et al*. (1998) to be matched at 11 months, but when each material does fail the locus of failure is likely to differ. Egan *et al*. (1996) found that with chemically cured composites the majority failed adhesively at the enamel/adhesive interface. Bishara *et al*. (1999) found that light-cured composite predominantly failed adhesively at the adhesive/bracket interface. It seems likely that the difference in bonding material used in this study and that of Hobson *et al*. (1999) is the most likely reason for the different patterns of bond strength observed.

The Weibull analysis allowed an estimation of the characteristic strength required for 5 and 10 per cent probabilities of failure under loading—a range of failure rate widely held to be clinically acceptable. Upper incisors required less than half the stress of any other tooth type for failure to occur either at 5 or 10 per cent probability. This difference was statistically significant.

The reason that different tooth types should exhibit different shear bond strengths and probabilities of failure at a given stress is not fully known. It seems likely that differing enamel anatomy is a contributory factor. Whittaker (1982) found premolar teeth contained relatively greater proportions of aprismatic enamel, which may adversely affect bond strength and survival. Mattick (1996) noted that etch pattern differed between tooth types. Hobson and Mattick (1997, 1998) and Mattick and Hobson (1997, 2000) further confirmed that *in vivo* and *ex vivo* etch patterns differ significantly between different tooth types and between opposing dental arches, although this latter difference was not significant.

Alternatively, the differences in shear bond strength found between different tooth types may relate to gross anatomical variability. Teeth with a highly variable morphology will demonstrate inconsistent adhesive film thickness. It may be that certain tooth types have greater morphological variation than others thereby generating a more variable adhesive film thickness and altered bond strength characteristics.

Conclusions

The results of this study confirm that significant differences in bond strength exist between teeth of different tooth-type series. Canine and premolar teeth exhibited significantly higher shear bond strengths and significantly lower probabilities of failure at given levels of applied stress than incisors. Comparison of this study's findings with those from a previous study using a similar methodology, but different bonding materials, confirm that significant differences in magnitude and pattern of bond strength exist between differing orthodontic adhesive/bracket combinations.

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