Original Article

The relationship between base dimensions, force to failure, and shear bond strengths of bondable molar tubes

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ABSTRACT

Objectives: To compare forces versus failure and shear bond strengths, and to explore their association with the base dimensions of four currently available bondable molar tubes.

Materials and Methods: Tubes were bonded to hydroxyapatite discs using a conventional light-cured adhesive and were tested to shear failure with the Instron Universal testing machine. Results were analyzed using the Kruskal-Wallis test and regression and survival analyses.

Results: No statistical difference was observed between the four groups globally in terms of force to failure ($P = .059$) and bond strength ($P = .179$). However, regression analysis showed that each 1 mm² increase in base surface area required an additional force of 3.11 N to debond the tube. Survival analysis showed that the tube with the greatest base dimensions had the best survival with increasing force to failure.

Conclusions: Although a relationship was demonstrated between force to failure and base surface area, it was not a simple one. No statistically significant relationship was found between bond strength and base surface area. (*Angle Orthod.* 2012;82:536–540.)

KEY WORDS: Bonding; Molar tubes; Shear bond strengths; Force to failure; Base surface area

INTRODUCTION

Bonding of attachments to molars has become increasingly popular in recent years because of the advantages that bonded molar tubes offer compared with bands. Advantages include greater time efficiency with no need for separation, elimination of band spaces that may appear post treatment, reduced contamination risks, more rapid placement, greater patient comfort, a more esthetic appearance, decreased risk of decalcification that may accompany loose bands, and easier detection of caries resulting from greater visibility of the enamel.[1]

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A bonded attachment must be able to withstand the shear, tensile, peel, and torsional forces generated during treatment, as well as the dynamic forces transmitted to the teeth during mastication and in occlusion.[2] An inability to successfully resist these forces results in bond failure. However, very high bond strengths are counterproductive because this hinders the removal of attachments at the completion of treatment, creating the potential for patient discomfort and enamel damage.[3] High bond failure rates have been reported[4–7]; these may result from orthodontic and masticatory forces, or from moisture contamination during the bonding process due to isolation difficulties.[8] Manufacturers have sought to address bond failure through improvements in adhesive technology and attachment design. Improvements have included increased base dimensions and changes in base design.

The aim of this study was to compare the shear bond strengths of four currently available molar tubes using a standardized bonding protocol.[9] Three null hypotheses were tested: (1) There are no differences in shear forces to failure, or in shear bond strengths, between the four tubes; (2) base surface area does not influence shear force to failure; and (3) modifying the base surface material using a polymeric material does not improve shear bond strength.

MATERIALS AND METHODS

Four bondable 0.022-inch slot lower first molar tubes were tested; 25 tubes were included in each group (n = 100 in total). The four tubes were labeled Tubes A through D with details as follows:

- Tube A (Quick>2.0 Big Foot molar tube, Forestadent, Pforzheim, Germany) had an enlarged base, which was developed with an increased surface area to increase bond strength.
- Tube B (Lo-Rider molar tube, TP Orthodontics Inc, La Porte, Ind) was a low profile tube with an 80-gauge mesh translucent polymer base. The polymeric base enhances light penetration during curing with the intention of improving bond strength.
- Tube C (Low Profile molar tube, American Orthodontics, Sheboygan, Wis) had an 80-gauge mesh on a photo-etched pad. The attachment had a lower profile, which may improve bond strength by reducing the potential for debonding under occlusal loading.
- Tube D (Victory Series molar tube, 3M Unitek, Monrovia, Calif) had a micro-etched 80-gauge mesh base, along with a buccal indent for positioning. It was used as a clinical standard based on its clinical popularity.

The 100 tubes were bonded to 25 hydroxyapatite discs, with a tube placed in each of the four quadrants of a disc sequentially in opposing pairs. A clinically popular adhesive system comprising etch gel, primer, and adhesive (Transbond XT, 3M Unitek) was used in accordance with a standardized bonding protocol.[9] Each disc was polished for 15 seconds with pumice and water slurry and was washed and dried using an oil-free triple syringe. Etch gel was applied to the disc for 30 seconds, after which the surface was washed and dried with the triple syringe until a frosty white appearance was observed. Resin primer was applied to the etched area using a microbrush applicator and was cured for 10 seconds with a visible blue curing light (XL 3000, B228137, 3M Unitek). Adhesive resin was placed onto the tube base from the syringe, and a plastic spatula was used to spread the material evenly over the attachment base, which then was placed carefully onto the bonding surface of the hydroxyapatite disc using bracket-holding tweezers. Excess composite resin was expressed from the underside of the tube under pressure during the seating procedure, and the resulting "flash" was removed. The attachment was cured with visible blue light for a total of 40 seconds—10 seconds each on the mesial, distal, gingival, and occlusal sides of the attachment. Light intensity was tested between curing episodes using the integral intensity monitor. Discs were incubated in distilled water for 24 hours at 37°C before bond strength testing was conducted.

A single operator performed all tests using a standardized protocol. Force to failure was tested in shear mode using a metal jig in the Instron Machine (Instron Ltd, High Wycombe, UK). Each hydroxyapatite disc was placed in the jig and a shear force applied by a sliding blade approaching the disc-tube interface vertically with the blade at the tube-substrate interface. The blade was driven at a crosshead speed of 1 mm/min. and the force at which bond failure occurred was recorded in Newtons (N).

To calculate bond strength, the surface areas of the attachment bases were estimated by measuring base length and breadth using Digital Vernier Calipers (Mitutoyo Digital Vernier Calipers, Andover, UK) and multiplying the two values to obtain the base surface area in mm^2. Base surface areas for five tubes of each type were calculated in this manner, along with mean values. The force in Newtons (N) at which bond failure occurred was divided by the surface area of the bracket base in mm^2 to obtain bond strength in MegaPascals (MPa).

Initial examination of the results showed outlying values for bond strength and force to failure; therefore the *median* value for each group was reported, in addition to the *mean*. The Kruskal-Wallis test was used for comparison between groups, and regression analysis was used to investigate the relationships between bond strength and base surface area. Survival analysis tested for differences in the proportions of tubes surviving at given force levels.

RESULTS

Force to failure data are shown in Table 1. Tube A had the highest *mean* force to failure at 130.17 N (95% confidence interval [CI], 104.71 to 155.63 N). The lowest *mean* force to failure was recorded with Tube C at 90.34 N (95% CI, 77.95 to 102.72 N). Differences in *mean* force to failure values were not statistically significant ($P = .059$), but results were considered borderline to the $P = .05$ level of significance.

Bond strength data are presented in Table 2. The highest *mean* bond strength of 6.01 MPa (95% CI, 4.76 to 7.26 MPa) was observed for Tube D, and the lowest *mean* bond strength of 4.60 MPa (95% CI, 3.70 to 5.49 MPa) was observed for Tube A. Differences in bond strength for the four groups were not statistically significant ($P = .179$).

Regression analysis, using the bondable surface area as the independent variable, showed a highly significant relationship between surface area and force to failure ($P = .005$). The regression coefficient showed that for every 1 mm^2 increase in surface area,

Table 1. Mean Force to Failure (Newtons) for the Four Molar Tubes Tested[a]

Molar Tube Type	Mean, Newtons	95% Confidence Interval	SD	Median	Minimum	Maximum
Lo-Rider	100.46	79.14 to 121.79	51.67	81.80	44.30	198.10
Big Foot	130.17	104.71 to 155.63	61.68	116.70	63.70	300.40
Victory	95.03	75.28 to 114.78	47.84	78.40	40.80	250.30
Low Profile	90.34	77.95 to 102.72	30.01	94.30	34.60	140.10

[a] SD indicates standard deviation.

3.11 N (95% CI, 0.97 to 5.25 N) greater force was required to debond the tube (Table 3).

Table 4 and Figure 1 illustrate survival with increasing force to failure. A useful way to interpret the survival data in Figure 1 is to consider the percentages of each tube type surviving a given force. For example, at a force of 100 N, it was estimated that 64% of Tubes A, 48% of Tubes C, 40% of Tubes D, and 36% of Tubes B would survive.

DISCUSSION

Although it might have been considered more ideal to have used extracted molar teeth as substrate, their availability is limited, morphology and fluoride content are variable, and concerns have been expressed about sterilization of the teeth before use, storage problems, and human tissues legislation.[10, 11] The use of bovine teeth has been shown to produce abnormally low bond strengths.[11] For these reasons, the molar tubes were bonded to hydroxyapatite discs, which have been shown by previous laboratory researchers to be acceptable biomimetic alternatives.[10,11] A standardized bonding protocol was followed[9]; bonding was carried out in a dry field, and all testing of bond strengths was carried out at least 24 hours later after storage in distilled water at 37°C to permit attainment of maximum bond strength in a simulated oral environment without risk of desiccation.[9,11,12] Transbond XT was used as the bonding agent in line with other bond strength studies, including those conducted using molar tubes.[9–18]

Force to failure data revealed the lowest *median* value with Tube D (78.40 N), although Tube C had the lowest *mean* value (90.34 N). The highest *mean* and *median* values were shown with Tube A (130.17 N and 116.70 N, respectively). The differences were not statistically significant ($P = .059$), although results approached borderline significance and are considered worthy of closer investigation.

Differences in testing methods make comparisons between studies difficult, with some studies reporting data only in MPa, without quoting the base surface area and force to failure values.[19,20] To overcome this, it has been suggested that a standardized protocol should be followed to permit valid comparisons.[9] Where bond strengths (MPa) and base surface areas are quoted, it was possible to retrospectively calculate forces to failure. This enabled mean force to failure values to be determined from data from two previous bond strength studies as 158.08 N,[17] which is higher than the mean force to failure values achieved in the current study (90.34 N to 130.17 N), and 128.47 N,[18] which is comparable with findings of the current study.

Bond strength takes into account the effect of base surface area on force to failure. The highest *mean* (6.01 MPa) and *median* (4.96 MPa) bond strengths were shown with Tube D. This tube had the smallest base surface area of the four molar tubes tested (15.81 mm^2) and the lowest *median* force to failure (78.40 N). In contrast, Tube A had the highest *median* force to failure (116.70 N) and the largest base surface area (28.35 mm^2) but the lowest *mean* bond strength (4.60 MPa). However, differences in bond strength between the four groups of tubes were not statistically significant. The *mean* bond strengths reported in the current study (4.60 to 6.01 MPa) compare favorably with those documented in previous research, which quoted *means* in the range of 3.04 to 7.65 MPa.[17,18,20]

Tube D had the least contoured base surface compared with the other three groups. This may have resulted in decreased thickness of adhesive between the base and the substrate, and may have contributed to the higher bond strength. In contrast, Tube A, with the greatest base contour, gave the lowest bond strength; this may have resulted in part from increased thickness of adhesive present between the base surface and the substrate. Although such variations in adhesive thickness due to base curvature could not

Table 2. Mean Shear Bond Strengths (MPa) for the Four Molar Tubes Tested

Molar Tube Type	Mean, MPa	95% Confidence Interval	SD	Median	Minimum	Maximum
Lo-Rider	4.73	3.73 to 5.74	2.43	3.85	2.09	9.33
Big Foot	4.60	3.70 to 5.49	2.18	4.12	2.25	10.60
Victory	6.01	4.76 to 7.26	3.03	4.96	2.58	15.83
Low Profile	4.62	4.00 to 5.26	1.54	4.83	1.77	7.17

Table 3. Regression Equation With Bondable Surface Area as the Independent Variable and Force to Failure as the Dependent Variable[a]

	Unstandardized Coefficients			
	B	Standard Error	P Value	95% Confidence Interval for B
Constant	37.93	23.40	.108	− 8.50 to 84.36
Surface area	3.11	1.08	.005	0.97 to 5.25

[a] Adjusted R^2 = 0.069.

be controlled, these values are similarly variable in clinical practice. Careful bonding technique eliminated excess resin at the base periphery, which would have added to adhesive surface area.

Although it has been suggested that brackets that allowed better penetration of light would produce higher bond strengths,[21] this suggestion was not supported in the current study by consideration of Tube B with its polymeric base specifically designed to allow greater light transmission during curing. The tube demonstrated the second lowest median force to failure (81.80 N) and the lowest median bond strength (3.85 MPa).

Studies have suggested that bond strengths of 5.9 to 7.8 MPa are clinically acceptable.[22,23] In the current study, bond strength ranged from 4.60 to 6.01 MPa, and only the control tube (Tube D) was within the range suggested as the benchmark.

Survival analysis showed that 75% of Tubes B would be retained at a force of 58.30 N; 75% of Tubes A at 89.40 N; and 75% of Tubes D at 60.90 N; 75% of Tubes C would be expected to remain in situ at 66.20 N. Tube A demonstrated consistently superior survival over the other tubes when force levels of 75 N, 100 N, and 150 N were considered. This may reflect the increased base surface area, as suggested by the regression analysis.

Previous workers achieved 90% survival of sandblasted and nonsandblasted molar tubes at mean bond strengths of 1.76 and 1.66 MPa, respectively.[19] In the current study, bond strengths achieved for 90% survival of molar tubes were higher, ranging from 1.94 to 3.09 MPa. The range of clinical bond strengths suggested by Reynolds (1975) equates to a force to failure range between 63 and 109 N.[22] The tubes used in the present study had median force to failure values that closely approximated to this range (median, 78.40

to 116.70 N). When survival analysis data were considered, 50% survival for tubes tested was in the range of 78.40 to 116.70 N. Thus a significant proportion of tubes would fail within the force to failure range previously suggested.[22]

Several factors must be considered when these results are interpreted. There appears to be a relationship between base surface area and force to failure, with regression analysis showing that for every 1 mm^2 increase in surface area, a 3.11 N greater force would be required to debond the tube (P = .005). This contrasts with the findings of others, who suggested that there is no relationship between bond success and base surface area.[12,22,24] However, when bond strengths were compared between the four groups, no direct relationship was noted (P = .179). Indeed, the tube with the smallest base (Tube D) demonstrated the highest *median* bond strength. This apparent paradox demonstrates that interpretation of any relationship between base size and bond failure is dependent on the method used to represent success of a directly bonded attachment.

From a clinical standpoint, it is the force to failure that is of greatest interest because it represents the greatest occlusal force that the attachment would be able to resist before failure occurs.[4,5,8] As a result, there seems to be a relationship between base size and force to failure. For this reason, Tube A with its enlarged base may fulfill the manufacturer's claims. However, the relationship between base size and force to failure clearly is not a simple one, because an increase in base surface area does not result in a linear increase in force to failure. Findings of the current study suggest that when bond failure is considered, it would be more informative to present data for *both* force to failure (N) and bond strength (MPa), because results may conflict.[9]

Table 4. Force Levels (Newtons) at Which 25%, 50%, and 75% of the Tubes Would Survive

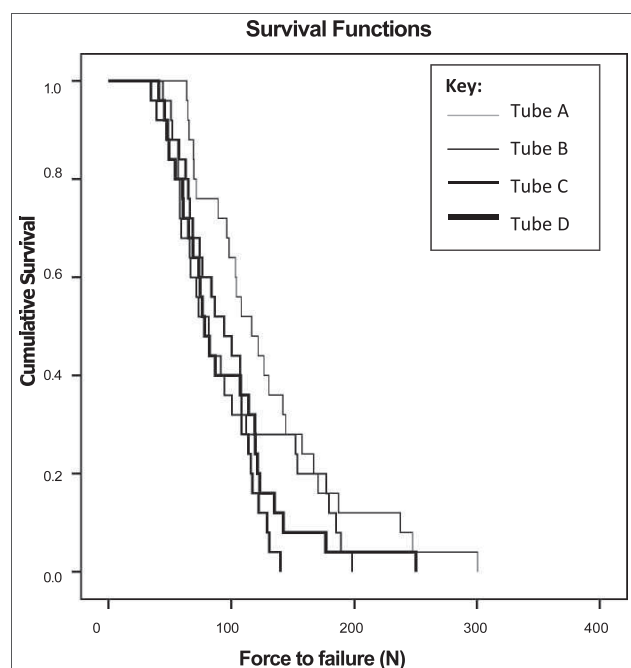|	25% Survival		50% Survival		75% Survival	
Tube Type	Estimate	Standard Error	Estimate	Standard Error	Estimate	Standard Error
Lo-Rider	152.40	37.94	81.80	9.33	58.30	1.87
Big Foot	157.70	17.94	116.70	14.82	89.40	20.06
Victory	119.70	5.13	78.40	6.33	60.90	8.16
Low Profile	113.90	4.22	94.30	13.82	66.20	4.34
Overall	123.30	6.93	94.30	8.30	65.50	2.51

Figure 1. Survival analysis data for the four molar tubes tested.

CONCLUSIONS

- Lack of statistically significant differences in force to failure ($P = .059$) and shear bond strength ($P = .179$) between the four tubes indicates that the first null hypothesis cannot be rejected.
- A relationship between base surface area and force to failure was shown, with every 1 mm² increase in base surface area resulting in an increase in force to failure of 3.11 N. Hence, the second null hypothesis is rejected in favor of the alternative hypothesis that increased surface area does result in increased force required for failure.
- Tube B with its polymeric base did not outperform the other tubes. The third null hypothesis cannot be rejected.

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