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Shear bond strength of orthodontic attachments bonded to impacted teeth under *in vivo* and *in vitro* conditions

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Structured Abstract

Objectives – To evaluate and compare the shear bond strength (SBS) of stainless steel and gold-plated attachments to impacted lower third molars *in vivo* and *in vitro* with a light-cured orthodontic resin.

Setting and Sample Population – Sixteen patients with bilaterally full soft tissue impaction of lower third molars were recruited on a voluntary basis from an oral and maxillofacial surgery department.

Materials and Methods – A split-arch technique was used. Following surgical exposure of the crown, the tooth was luxated but not extracted. Then, two attachments (one stainless steel button and one gold-plated eyelet) were bonded to the labial enamel surface of the loosened tooth. Five minutes later, the luxated tooth was removed from its socket. In each patient, the impacted tooth on the other side was extracted, and attachments were bonded *in vitro*. The SBSs of the attachments were evaluated. For comparison, analysis of variance and multiple range tests were used ($\alpha = 0.05$).

Results – Statistically significant differences were evident in attachment adhesion to the impacted tooth surfaces among the four groups ($p < 0.001$). Superior SBS values were obtained for stainless steel button groups bonded *in vitro*. The mean bond strengths of the groups bonded *in vitro* were better than those of the same groups bonded *in vivo*.

Conclusions – Although the *in vitro*-bonded groups showed higher SBS values, adequate bond strength is possible with stainless steel buttons bonded *in vivo*.

Key words: bond strength; impacted teeth; *in vitro* bonding; *in vivo* bonding; orthodontic attachment

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Introduction

Ever since the introduction of direct bonding for impacted teeth, orthodontic management of unerupted teeth has been a routine procedure (1). Following surgical exposure, tooth movement is accomplished by the bonding of an orthodontic attachment to the exposed tooth surface and the application of traction force. The bonding of the orthodontic attachment on the tooth may be performed at the time of surgical exposure or at a later date (2). Although it has been shown that bonding at the time of exposure is superior to bonding at any other time (2), isolating and controlling contamination at that stage can be challenging, and this tooth-isolating factor could cause bond strength to deteriorate (3).

The bond strength properties of adhesive resins and different orthodontic attachments have been extensively researched in the laboratory, but several parameters in the oral environment are impossible to reconstruct *in vitro* (4). Therefore, some *in vivo* debonding devices that can be used for determining bond strengths in the oral environment were described and used (5–7). Although actual *in vivo* bond strengths can be measured with these types of devices, their use on unerupted teeth and elsewhere in the mouth can be difficult. Moreover, to our knowledge, there is no other study published that compares the mean shear bond strengths of *in vivo*- and *in vitro*-bonded attachments on impacted teeth. Therefore, the purpose of this study was to compare the shear bond strengths (SBSs) of two types of orthodontic attachments (stainless steel button and gold-plated eyelet) bonded under *in vivo* and *in vitro* conditions with a light-cured orthodontic adhesive on impacted lower third molar teeth. The mode of bond failure sites was also investigated.

Material and methods

Sixteen patients with bilateral fully impacted lower third molars were used for this study (Fig. 1a). The sample size for the present study was calculated based on a significance level of 0.05 and a power of 95% to detect a meaningful difference between the mean SBSs of the groups. The power analysis (NCSS 2007 and PASS 2008 Statistical Software, NCSS, LLC, Kaysville, UT, USA) showed that 14 samples (teeth) were required for each group. To compensate for possible dropouts during the trial, we decided to select 16 patients (32 impacted teeth) for the present study.

The mean age of the entire sample was 19.8 years (range, 17.2–25.1). After receiving ethics committee approval (OMU, Medical Research Ethics Committee 2010/60, No: 125), we sought and obtained informed consent from the patients. Sixteen patients were randomly divided into two groups. In the first group (eight patients), impacted lower right third molars were used to bond orthodontic attachments *in vivo*, and on the left side, impacted third molars were extracted for use in the *in vitro* portion of the study. In the second group, the procedure was reversed, that is, the impacted third molars on the left side were used for *in vivo* bonding in the second group. In both groups, the following surgical and bonding procedures were applied.

In vivo bonding

After obtaining local anaesthesia via inferior alveolar and long buccal nerve blocks, a full-

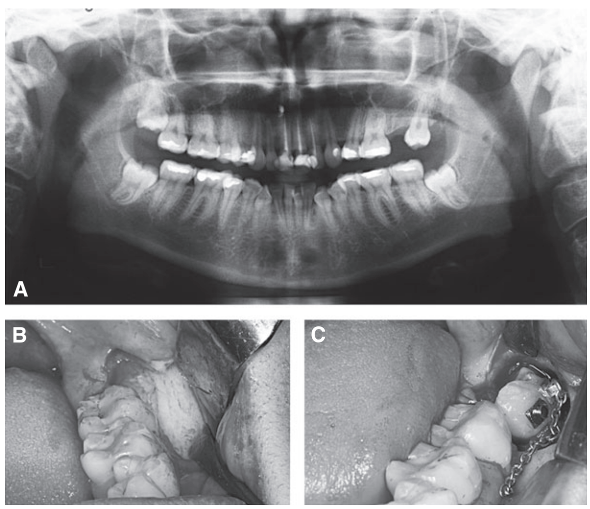

Fig. 1. (a) Panoramic radiograph of a patient; (b) intra-oral view of the same patient after mucoperiosteal flap reflection; (c) orthodontic attachments on the impacted lower third molar just before extraction.

thickness triangular mucoperiosteal flap was reflected starting just distal to the mandibular second molar (Fig. 1b). Then, the buccal bone covering the impacted third molar crown was carefully removed by means of an electronic handpiece and rose bur. Following exposure of the crown, the tooth on 1 side was luxated with an elevator but not extracted. Next, the superior part of the mucoperiosteal flap was kept away with a retractor; thus, the buccal crown surface of the third molar was exposed sufficiently for orthodontic attachment bonding. The exposed labial surfaces were etched with a 37% phosphoric acid gel for 30 s, rinsed with deionized sterile water for 10 s and dried with compressed air. Then, two attachments were bonded to the labial enamel surface of the tooth (Fig. 1c). Sixteen stainless steel orthodontic buttons (3M Unitek, Monrovia, CA, USA) and 16 gold-plated eyelets (Ortho Technology, Tampa, FL, USA) were used in this portion of the study. Both attachments were rectangular and had the same curved mesh bases. One button and one eyelet were bonded to the buccal surface of each impacted molar, with maximum care taken to keep the buccal enamel surface from contamination by saliva and blood. In the first patient, the stainless steel button and gold-plated eyelet were bonded to the mesiobuccal and distobuccal sides of the impacted molar, respectively. These sides were alternated with each consecutive patient.

For bonding, a Transbond XT adhesive (3M Unitek) was used. The adhesive-resin-loaded attachments were lightly pressed onto the enamel surface with a bracket holder, and any excess adhesive was carefully removed with a dental scaler. Attachments placed on the impacted tooth surface were exposed to a halogen-curing lamb with a light intensity of approximately 400 mW/cm^2 (Ortholux XT; 3M Unitek) for 20 s (10 s for each interproximal surface) according to the manufacturer's instructions. Then, the mucoperiosteal flap was freed, and the bonded tooth surface was carefully recovered and left undisturbed. Five minutes later, the previously luxated tooth was carefully removed from its socket by an elevator approaching from the mesial or distal proximal surface, and stored in distilled deionized water at 37°C for 24 h.

In vitro bonding

One week later, the tooth opposite to each impacted tooth used for *in vivo* bonding was directly extracted for use in the *in vitro* portion of this study. The identical bonding procedure was used to bond 16 stainless steel orthodontic buttons and 16 gold-plated eyelets to the labial surfaces of the extracted lower third molar teeth under *in vitro* conditions. In this portion of the study, acid-etching, rinsing, drying and light-curing times were exactly the same as those for the *in vivo* portion of the study.

A jig was specially constructed for mounting the tooth-orthodontic attachment combination in a position where the button and eyelet bases were parallel to the cylindrical surface and the tooth was at the centre of the plastic moulding cup, which was filled with dental stone. A period of 5 min was allowed for initial setting before the mounted specimens were again placed in distilled water at 37°C for 24 h before being tested.

Bond strength testing

The SBSs of the attachments on each tooth were evaluated in a Lloyd LRX testing machine (Lloyd Instruments Plc, Fareham, Hampshire, UK) with a cross-head speed of 1 mm/min. The peak force levels were automatically recorded in Newtons (N) and used for the statistical analyses. For comparison with the literature, the mean SBSs of the groups were also converted in megapascal (MPa) by dividing the mean force values (Newtons) by the attachment base area (mm^2). The bonding surfaces for three attachments from each of two types were measured to the nearest 0.01 mm with a reflex microscope connected to a computerized video image analysis system. The bonding surfaces of three attachments from the two groups were measured, and the mean nominal surface areas calculated for the stainless steel and gold-plated attachments were 9.17 and 10.05 mm^2, respectively. The bond failure sites were also evaluated. After being tested, the separated assemblies were recovered and examined under an optical microscope at 20× magnification so that the site of failure could be determined. Adhesive remnant index (ARI) scores were used for the classification of failure sites (8).

Statistical analysis

The data were analysed with a statistical software package programme (SPSS V12.0; SPSS Inc., Chicago, IL, USA). Before descriptive and inferential statistical analysis, each dataset was analysed by the Shapiro–Wilk normality test. As the data were normally distributed in all groups, statistical analyses were performed using analysis of variance (ANOVA) and any significant differences revealed by this procedure were further investigated with Tukey's honestly significant difference (HSD) *post hoc* tests. ARI rating scores were subjected to the chi-square (χ^2) test for analysis of the failure sites. The level for statistical significance was set at $\alpha = 0.05$.

Results

The descriptive statistics for the SBSs of the groups tested are shown in Table 1. The stainless steel button group bonded *in vitro* was found to have the highest mean SBS (90.41 N). This was followed by the stainless steel button group bonded *in vivo* (64.63 N). The gold-plated eyelet group bonded *in vitro* had a mean SBS of 53.41 N, and the gold-plated eyelet group bonded *in vivo* had the lowest mean SBS (47.75 N).

Using the SBS as the dependent variable in a factorial ANOVA, a statistically significant interaction was found between the attachment type (button and eyelet) and the bonding condition (*in vitro* and *in vivo*) $F_{1,60} = 4.452$, $p = 0.039$. The results revealed that the SBS was significantly affected by the attachment type ($p < 0.001$) and the bonding condition ($p < 0.01$). In contrast, the SBSs of both attachments were not affected by the bonding sides ($p > 0.05$) within each group. In other words, there was no significant difference between the SBSs of the same attachment whether bonded on the mesiobuccal or the distobuccal surface of an impacted tooth.

ANOVA showed significant differences in the SBSs among the four groups ($p < 0.001$). Tukey's HSD tests revealed significant differences between the stainless steel button group bonded *in vitro* and the other three groups: the stainless steel button group bonded *in vivo* ($p < 0.01$), the gold-plated eyelet group bonded *in vivo* ($p < 0.001$) and the gold-plated eyelet group bonded *in vitro* ($p < 0.001$).

The chi-square analysis comparing the ARI scores (Table 2) indicated no significant differences among the four groups ($p > 0.05$). In both the stainless steel button and gold-plated eyelet groups bonded *in vitro*, the greatest frequency was observed at ARI scores of 2 (50 and 43.8%, respectively), whereas the button and eyelet

Table 1. **Descriptive statistics and bond strengths for each group (in Newtons)**

Bonding	Attachment	N	Mean (MPa)*	Range (Min.–Max.)		SD	$p^{\dagger}$
In vivo	Stainless steel button	16	64.63 (7.05)	30	102	20.45	A
	Gold-plated eyelet	16	47.75 (4.75)	28	77	16.57	A
In vitro	Stainless steel button	16	90.41 (9.86)	62	129.5	23.10	B
	Gold-plated eyelet	16	53.41 (5.31)	21	82	15.13	A

*Mean SBSs of the groups were also presented in MPa by dividing the mean force values (in Newtons) by the stainless steel button (9.17 mm^2) and gold-plated eyelet (10.05 mm^2) base areas.

†Groups shown with the same letters were not significantly different at the $p = 0.05$ level according to Tukey's HSD test.

Table 2. **Frequency and percentage occurrence (%) of the Adhesive Remnant Index (ARI) for each group tested**

Bonding	Attachment	N	ARI 0 (%)	ARI 1 (%)	ARI 2 (%)	ARI 3 (%)
In vivo	Stainless steel button	16	4 (25.0)	6 (37.5)	5 (31.2)	1 (6.2)
	Gold-plated eyelet	16	4 (25.0)	8 (50.0)	3 (18.8)	1 (6.2)
In vitro	Stainless steel button	16	1 (6.2)	5 (31.2)	8 (50.0)	2 (12.5)
	Gold-plated eyelet	16	2 (12.5)	4 (25.0)	7 (43.8)	3 (18.8)
Total		64	11 (17.2)	23 (35.9)	23 (35.9)	7 (10.9)

ARI scores: 0 = no adhesive left on the tooth, 1 = less than half of the adhesive left on the tooth, 2 = more than half of the adhesive left on the tooth and 3 = all adhesive left on the tooth.

groups bonded *in vivo* displayed the greatest frequency at an ARI score of 1 (37.5 and 50%, respectively).

Discussion

This study was designed to simulate a clinical situation, because the bonding of impacted teeth, particularly pre-molars and molars, is performed at the time of surgical exposure, with a concomitant high risk of blood and saliva contamination of the exposed enamel surface. Therefore, in the *in vivo* bonding portion of the study, orthodontic attachments were bonded to the buccal surfaces of impacted lower third molars with a light-cured orthodontic resin following surgical exposure. Then, bond strength measurements for both *in vivo*- and *in vitro*-bonded specimens were conducted in the laboratory, and the differences between the groups were evaluated.

It has been reported that the use of an eyelet attachment on an impacted tooth had a lower failure rate than the use of a conventional bracket (2). Therefore, orthodontic buttons and eyelets were used in this study.

In the present study, a split-arch protocol was used to minimize within-subject variability. To eliminate interexaminer variation, all surgical exposures and extractions were made by the same surgeon, and teeth in all groups were bonded by the same clinician. In spite of these efforts to minimize technique inconsistencies, it was impossible to blind the operator to the attachment being used. Nevertheless, as stated before, one of the aims of this study was to simulate an actual clinical situation.

In bond strength studies, the peak force level at failure is generally normalized by dividing it by the area of the attachment base. However, an average bond stress value may not shed much light on the failure pattern in the joint because of non-uniform stress fields within the adhesive resin layer (9, 10). Moreover, the base of orthodontic attachments generally has mechanical retention structures (mesh, milled, casted etc.) hampering effective measurement of the base area. As a high proportion of bonded attachments in this study failed due to component failure (ARI scores 1 and 2) and the attachments had mesh bases, the SBSs were presented in Newtons and these values were used for the statistical analyses. However, as stated before, the mean SBS values of the groups were also converted in megapascals to compare the results of this study with the literature.

The mean SBS of the light-cured Transbond XT adhesive used for the bonding of both attachments was lower than that observed in some previous *in vitro* studies (11–16). This points to the importance of other variables, such as the testing techniques, substrates, materials and methods used in determining the bond strengths. Therefore, it is difficult to draw meaningful conclusions from comparisons of the different studies, due to the inconsistencies.

The results of the present study showed that the mean SBSs of the orthodontic attachments decreased significantly when the bonding was performed *in vivo*. This effect of *in vivo* bonding on bond strength for different adhesive and bracket materials was also found in several other studies (4, 6, 7, 17, 18). The reduction in the mean SBSs was around 28.5% for the stainless steel button and 10.6% for the gold-plated eyelet groups in this study. The decrease in the SBSs of *in vivo*-bonded attachments relative to those that were bonded *in vitro* may possibly be explained by the contamination from saliva and blood, and the high level of moisture in the oral environment. Another reason for this might be due to the difficulty encountered by the operator in bonding the attachments to the impacted molars located at the end of the lower arch. Although maximum care may be taken to prevent contamination, these factors are likely to adversely affect the adhesion of the resin to the etched enamel surface of impacted molar teeth during *in vivo* bonding. This assumption was also supported by the ARI scores of the groups. Both buttons and eyelets bonded *in vivo* showed ARI scores of predominantly 1 and 0 (together, 68.8%) in this study. These findings indicate that residual adhesive resin on the enamel surfaces of the *in vivo*-bonded groups was less than that of the *in vitro*-bonded groups.

As stated before, a direct comparison between the results of the present study and those of others is somewhat difficult because there is no similar study in the literature. However, the present results may, at least in part, be compared with those of previous studies in which similar *in vitro* bonding procedures, test methods and materials were used. In this study, the mean SBSs for stainless steel buttons bonded *in vitro* with Transbond XT resin were higher than those reported by Nur et al. (19), who reported an average value of 6.6 MPa for the same adhesive resin and round-based stainless steel buttons bonded to extracted molar teeth. Mean shear bond strengths higher than those obtained in the present study were recorded by Nemeth et al. (18), who tested mesh-based stainless steel buttons bonded with Transbond XT resin on extracted human molars. Apart from the aforementioned variations between the bond strength studies, the lower mean SBS values of orthodontic buttons and eyelets may be due to the variations in buccal surface morphology and the immature content of the outermost layer of enamel of the impacted (unerupted) lower third molar teeth used in this study (20, 21). As is known, unerupted teeth have compositional and structural differences in their enamel minerals when compared with mature (erupted) teeth (20, 22, 23). However, it should also be stated that several studies have reported that bond strength does not appear to be significantly affected by the post-eruptive enamel maturation process (24–26).

Although *in vitro* bond strength studies may not always reflect intra-oral conditions and be predictive of clinical performance of the attachments and adhesives, they are valuable and can be an acceptable methodology to determine future *in vivo* comparative conditions. Moreover, there is controversy in the literature about the minimum *in vitro* bond strength necessary to predict clinical success. It has been reported that a maximum tensile bond strength of 60–80 kg/cm^2 (5.9–7.9 MPa) would be adequate to resist treatment forces, but that *in vitro* experiments with brackets giving tensile test levels of 50 kg/cm^2 (4.9 MPa) have been proven clinically acceptable (27). Forces required to move a tooth orthodontically through bone usually vary between 0.05 and 0.40 kg. (28) It has also been reported that 10 lb (4.5 kg) of applied orthodontic force is rarely exceeded in clinical conditions (29). With a bond area around 10 mm^2, as used in this study, 10 lb of activation would translate to a force of around 4.5 MPa on the bracket ($4.5\ kgf/10\ mm^2 = 4.41$ MPa). Although the groups in this study generated mean SBSs (4.75–9.86 MPa) within the range stated in the literature (29), the buttons and eyelets which had SBS values lower than 4.5 MPa might cause failure of the bond during impacted pre-molar and molar traction. Therefore, attachments with wider base structures should be used during the orthodontic traction of impacted posterior teeth. However, further clinical studies are needed to investigate the bond strengths of the different orthodontic attachment and adhesive combinations on the surfaces of impacted teeth.

Conclusions

The mean SBSs of orthodontic stainless steel buttons and gold-plated eyelets bonded on the buccal surfaces of impacted mandibular third molars under *in vivo* conditions were significantly lower than those bonded *in vitro*.

The ARI scores indicated that the predominant failure mode shifted from the bracket/adhesive interface *in vitro* to the adhesive/enamel interface when the attachments were bonded *in vivo*.

Clinical relevance

Surgical exposure and bonding of an attachment on the impacted tooth surface are generally performed at the same visit. During this *in vivo* procedure, blood and saliva contamination deteriorates the bond strength of the orthodontic attachments. However, all phases of the bond strength studies are generally performed under *in vitro* conditions. A comparison between the *in vitro* and *in vivo*-bonded stainless steel buttons, and gold-plated eyelets on impacted teeth revealed that deterioration levels of bond strengths were significantly different. From 10 to 30%, decrease in the mean bond strengths was determined when bonding performed *in vivo*.

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