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A comparison of tungsten-quartz-halogen, plasma arc and light-emitting diode light sources for the polymerization of an orthodontic adhesive

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SUMMARY This study investigated whether there were differences between the debond stress and adhesive remnant index (ARI) of an adhesive cured with three different orthodontic light sources. Sixty sound premolar teeth were divided into three groups of 20. A standard pre-adjusted edgewise premolar bracket (Victory Series™) was bonded to each tooth using a light-cured orthodontic adhesive, Transbond XT™. Group 1 (control) specimens were cured with an Ortholux XT™ (tungsten-quartz-halogen bulb) light for 20 seconds, group 2 with an Ortho lite™ (plasma arc) for 6 seconds and group 3 with an Ortholux LED™ light-emitting diode for 10 seconds. The specimens were debonded 24 hours later using a universal mechanical testing machine, operating at a crosshead speed of 0.5 mm minute^{-1}.

The Weibull modulus and a Logrank test showed no statistically significant differences between the three groups for debond stress. The ARI was assessed at ×10 magnification. The ARI scores for group 2 were significantly different ($P < 0.01$) from those of groups 1 and 3 (between which there was no significant difference). For group 2 there was a greater tendency for failure to occur at the adhesive/tooth interface than for the other two groups. There appears to be no reason why any of the three types of light source cannot be used in orthodontics. Polymerization, as effective as that produced by conventional bulb light sources, was obtained with the short exposure times recommended for the plasma arc or light-emitting diode sources.

Introduction

In fixed appliance treatment one of the most important requirements is correct bracket positioning (Bennett and McLaughlin, 1997). The use of light-cured adhesives has become popular since they provide increased working time (Sonis, 1988), and aid correct bracket positioning. The use of light-cured adhesives in orthodontics was first reported by Tavas and Watts (1979). Unfortunately, as a result of conflicting reports comparing the bond strengths of light- and chemically-cured adhesives (Wang and Meng, 1992; Trimpeneers and Dermaut, 1996; Armas-Galindo *et al.*, 1998) the use of light-cured products is not as widespread in orthodontics, as in restorative dentistry.

The main advantage of light-cured adhesives is the ‘command setting’. However, this is also a disadvantage since the time required to initiate polymerization with a light source may seem inconvenient to clinicians. To reduce the bonding time, pre-coated brackets have been developed. These brackets have been shown to perform satisfactorily in the clinical situation (Ash and Hay, 1996). Also, to this end, new curing light technologies have been developed, which manufacturers claim reduce the curing time by one-third to one-half, relative to conventional tungsten-quartz-halogen bulb light-curing sources.

The main aim of this study was to compare the debonding stress for brackets bonded with the same light-cured adhesive system but cured with light sources that utilize different technologies for light production. The null hypothesis was that there is no difference in the debonding stress between the three light-curing systems. The second aim was to evaluate the bond failure site, to establish whether any differences in the failure site result from the use of these light-curing systems. The adhesive remnant index (ARI; Årtun and Bergland, 1984) was selected as a simple but informative semi-quantitative method to provide this information. The null hypothesis was that there is no difference in the distribution of ARI scores with different light-curing systems.

Materials and methods

Sixty sound premolar teeth, extracted for orthodontic purposes from patients under 18 years of age and living in an area with a non-fluoridated water supply, were collected and stored in distilled water. They were mounted in resin blocks with the long axis of each tooth set vertically. These specimens were divided randomly into three equal groups to comply with the recommendation of Fox *et al.* (1994) that at least 20 teeth per test be used for *ex vivo* bond strength testing.

A standard pre-adjusted edgewise lower premolar steel bracket (Victory Series™, 3M Unitek, Monrovia, California, USA) was used, as was a single light-cured adhesive product (Transbond XT™, 3M Unitek) to produce all specimens. Details of the group identities, according to the light sources used and the curing times are given in Table 1.

All light-curing units were characterized by the irradiance (mWcm^{-2}) and spectral band width (Δλ nm) with an intensity dependent upon wavelength. The sources used in the present study were representative examples of the conventional tungsten-quartz-halogen bulb, the plasma arc and light-emitting diode (LED) technologies (all three products are marketed by 3M Unitek):

1. Ortholux XT™, a tungsten-quartz-halogen bulb source with an irradiance of 400 mWcm^{-2}, emitting light in the range of 400–500 nm.
2. Ortho lite™, a plasma arc source with an irradiance of 2000 mWcm^{-2}, emitting light in the range of 400–500 nm.
3. Ortholux LED™, a blue LED source with an irradiance of 1000 mWcm^{-2}, emitting light in the range of 430–480 nm.

The absorbance spectrum for the initiator camphorquinone peaks at 470 nm, falling to 10 per cent of its value at 400 nm and at 520 nm (Pradham *et al.*, 2002). Ideally, for an optimum effect the radiance spectrum should match the absorbance spectrum.

A single clinically experienced operator (BT) carried out all bonding. The materials were used according to the manufacturer's instructions: the teeth were pumiced using fluoride-free pumice and water for 15 seconds applied with a rubber cup, then rinsed with water and dried in a stream of oil-free compressed air. The teeth were then etched for 15 seconds with 37 per cent orthophosphoric acid, washed with water for 20 seconds and dried using oil-free compressed air. A thin layer of primer was applied to the etched tooth surface with a microbrush. The bracket was loaded with adhesive and placed on the buccal surface with light pressure to extrude any excess adhesive, which was removed with a probe. The adhesive was cured using the times recommended by the manufacturer for each light source (Table 1).

The bonded specimens were stored in distilled water at 37°C for 24 hours before determining the debond force.

A universal mechanical testing machine (Model 4469, Instron Ltd, High Wycombe, Bucks, UK) was used to measure the debond force. A stainless steel loop applied the force to the bracket in a gingivo-occlusal direction, as outlined by Fox *et al.* (1994). This produces a stress vector with a predominant shear component. The test jig by which the specimen was attached to the stationary anvil allowed the specimen position to be adjusted in the *x–y* plane and then locked into position. This enabled the end of the loop to be placed precisely and consistently under the gingival tie wings of each bracket, to ensure that the distance between the surface of the tooth and the point of application of the force was consistent for every specimen. A crosshead speed of 0.5 mm minute^{-1} was used and the force required to dislodge the bracket measured to the nearest 0.1 N. The debond stress was calculated from this force and the bracket base area given by the manufacturer, 10.57 mm^2.

Table 1 Group identities. The light sources and curing times used for each group.

Group	Light-curing system	Curing Times
1 (control)	Ortholux XT™	10 seconds mesial, 10 seconds distal
2	Ortho lite™	3 seconds mesial, 3 seconds distal
3	Ortholux LED™	5 seconds mesial, 5 seconds distal

Debonding tests were conducted in air at ambient laboratory temperature (20 ± 2°C).

Following debond, each tooth was examined by a single operator (BT) at ×10 magnification using a binocular microscope (The Grey Five Forty, Grey, Norwich, Norfolk, UK). The bond failure site was recorded along with the ARI (Årtun and Bergland, 1984). This index consists of the following scoring:

1. 0 = no retained resin.
2. 1 = <50 per cent retained resin.
3. 2 = >50 per cent retained resin.
4. 3 = all resin retained with bracket imprint.

Statistical analyses were undertaken using Unistat 5.0 software (Unistat Ltd, London, UK) and Stata 7, Statistical Software for Professionals, (Statacorp LP, College Station, Texas, USA). Weibull analysis (Weibull, 1951) estimates of the survival function were undertaken to relate the probability of bond failure to the applied stress. This method of analysis was advocated by Fox *et al.* (1994). A Logrank test (Mantel, 1966) and the Kaplan–Meier non-parametric survival analysis (Kaplan and Meier, 1958) were also carried out, the latter as it assumes no underlying data distribution. The ARI data were analysed with chi-square tests.

Results

The results are shown in Tables 2 and 3 and the Weibull plot for each group in Figure 1. Cox–Snell residual diagnostic plots (Cox and Snell, 1968) are not presented but showed a reasonable fit to the Weibull regression model. The Weibull modulus was lowest for group 3 and highest for group 2. However, the difference between all three groups was small and the 95 per cent confidence intervals (CI) for the Weibull moduli overlapped, confirming no significant difference in the value for the three groups. The Logrank test showed no statistically significant differences between the three groups (P = 0.86). The proportion of brackets surviving as a function of stress is presented in Figure 2. Again, the three groups showed considerable overlap for the 95 per cent CI for the debond stress. The null hypothesis is accepted.

Table 2 Bond stress characteristics of the test groups.

Group	Debond stress (MPa)	Debond stress (MPa)	Weibull modulus	Correlation coefficient	95% confidence interval for the debond stress (MPa)
	Mean (standard deviation)	Maximum	(95% confidence interval)		
1 Ortholux XT™	6.83 (2.68)	15.74	7.48 (7.17 to 7.81)	0.96	5.64 – 7.75
2 Ortho lite™	7.14 (1.80)	11.55	7.64 (7.36 to 7.91)	0.98	6.29 – 7.98
3 Ortholux LED™	6.70 (2.25)	13.82	7.25 (6.84 to 7.62)	0.97	5.70 – 7.68

Table 3 Logrank test comparing the stresses recorded at debonding for each curing light.

Group	Total	Observed	Expected	$(O-E)^2/E$	$(O-E)^2/V$
1 Ortholux XT™	20	20	19.64	0.0065	0.010
2 Ortho lite™	20	20	21.88	0.162	0.27
3 Ortholux LED™	20	20	18.48	0.126	0.19
Total	60	60	60.00	0.298	

Mantel–Haenszel (Peto): chi-square statistic = 0.31.
Degrees of freedom = 2.
Right-tail probability = 0.86.

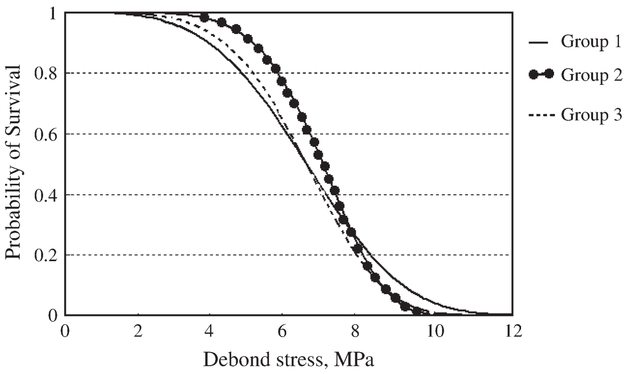

Figure 1 The Weibull plot for stress to failure for the three groups. Light sources: Group 1, Ortholux XT™ (tungsten-quartz-halogen bulb); Group 2, Ortho lite™ (plasma arc); Group 3, Ortholux LED™ (LED).

Table 4 shows the results of the Kaplan–Meier non-parametric comparisons, which again showed an overlap of the CI for the mean debond stresses.

To check the reliability of the ARI scoring, 20 randomly selected samples were scored independently and on two separate occasions by two investigators (BT and DS), to calculate the intra- and inter-rater reliability. There was complete agreement for scorings on both occasions by the first investigator and a single disagreement between the first and second scoring by the second investigator, resulting in an intra-rater kappa of 0.77, an indication of substantial agreement (Landis and Koch, 1977). With regard to inter-rater reliability, on the first occasion a single disagreement between investigators gave a kappa value of 0.77. However, on the second occasion there was 100 per cent agreement between the two investigators.

The bracket/adhesive interface was the predominant site of failure for all three groups. None had an ARI score of zero. In groups 1 and 3 the majority of specimens had an ARI score of 3 and in group 2 the majority of specimens had an ARI score of 2. Table 5 and Figure 3 show the distributions of ARI scores. The result of the chi-square test for the ARI scores and three light-curing systems is presented in Table 6. For group 2, significantly fewer ($P = 0.01$) brackets left resin with a full imprint of the bracket base on the tooth after debond. The null hypothesis was rejected.

Discussion

There was no statistical difference in debond stress between all three light sources. Orthodontists are mainly concerned with the minimum bond strength, below which a bond between the tooth and bracket is too weak to withstand forces applied to it during treatment. This minimum level is difficult to calculate due to the large variations in forces (for example, from different archwires, or from mastication) that a bracket has to endure over the course of an average orthodontic treatment time. It has been suggested that a minimum bond strength of 6 to 8 MPa should be adequate for most clinical orthodontic needs (Reynolds, 1975). According to this minimum requirement, all three light sources cured the adhesive to an equally satisfactory level. However, a note of caution has to be added, since stress values proposed by Reynolds (1975) are not evidence based, though they are frequently cited. If, in clinical practice the survival rate is satisfactory for brackets bonded to enamel by adhesive that is cured using light from a conventional tungsten-quartz-halogen source, then the results obtained with plasma arc and LED sources are expected to be equally satisfactory.

The time recommended to cure the adhesive was least with the plasma light and longest with the conventional tungsten-quartz-halogen curing light. Based on the manufacturer's curing instructions, nearly 5 minutes could be saved for every complete upper and lower arch bond-up using the plasma Ortho lite™ compared with the conventional tungsten-quartz-halogen bulb light source, Ortholux XT™. A shorter curing time may also reduce the risk of saliva contamination and further reduce the incidence of bond failure. The time saved with the Ortholux LED™ was marginally less. The reduced curing time achieved with

Table 4 Kaplan–Meier non-parametric quantiles of the survival function. (Quantiles indicate the proportion surviving at that stress.)

	Group 1 (Ortholux XT™) (95% CI)	Group 2 (Ortho lite™) (95% CI)	Group 3 (Ortholux LED™) (95% CI)
Mean	6.83 (5.65 – 8.00)	7.14 (6.34 – 7.92)	6.70 (5.71 – 7.68)
Quantile 1: 25%	7.37 (6.34 – 8.40)	7.38 (6.98 – 7.77)	7.01 (6.87 – 7.15)
Quantile 2: 50%	6.48 (5.28 – 7.68)	6.60 (6.38 – 6.82)	6.60 (5.57 – 7.64)
Quantile 3: 75%	5.34 (4.53 – 6.14)	5.90 (5.10 – 6.70)	4.83 (4.02 – 5.63)

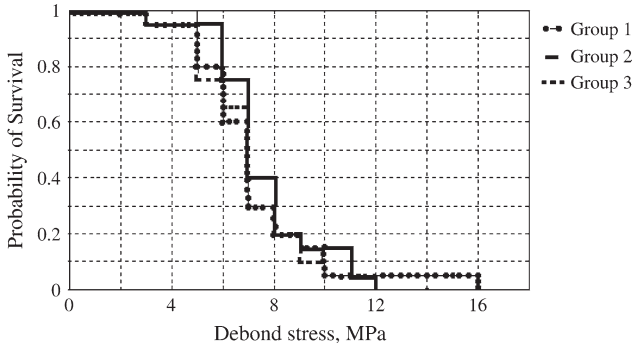

Figure 2 Survival as a function of stress for the three groups. Light sources: Group 1, Ortholux XT™ (tungsten-quartz-halogen bulb); Group 2, Ortholite™ (plasma arc); Group 3, Ortholux LED™ (LED).

Table 5 Frequency of adhesive remnant index (ARI) scores for the 20 specimens in each of the three groups. Light sources: Group 1, Ortholux XT™ (tungsten-quartz-halogen bulb); Group 2, Ortho lite™ (plasma arc); Group 3, Ortholux LED™ (LED).

Group	ARI score 1	ARI score 1	ARI score 2	ARI score 3
1	0	0	6	14
2	0	3	13	4
3	0	1	6	13

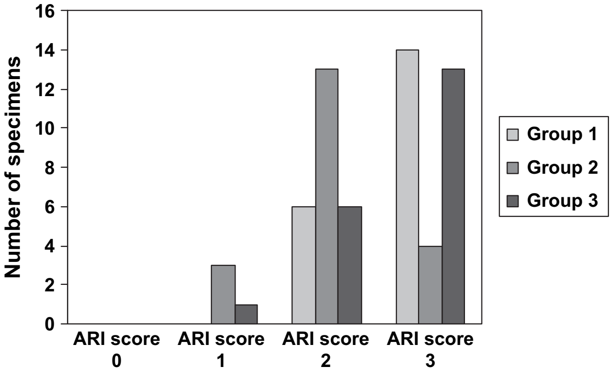

Figure 3 Distribution of the adhesive remnant index (ARI) scorings (*n* = 20) for each group. Light sources: Group 1, Ortholux XT™ (tungsten-quartz-halogen bulb); Group 2, Ortholite™ (plasma arc); Group 3, Ortholux LED™ (LED).

Table 6 Chi-square statistic on the cross tabulation of ARI score categories by the type of curing light. Light sources: Group 1, Ortholux XT™ (tungsten-quartz-halogen bulb); Group 2, Ortho lite™ (plasma arc); Group 3, Ortholux LED™ (LED).

Group	ARI score 1	ARI score 2	ARI score 3
1	1.33	0.65	1.30
2	2.08	2.61	3.88
3	0.083	0.65	0.69

Overall chi-square statistic = 13.29.
Degrees of freedom = 4.0000.
Right-tail probability = 0.01.

the newer technology lights is an advantage for clinicians which has to be balanced against the higher capital cost. Presently, they are nearly three times the price of conventional light sources. A busy orthodontic practice may find them a worthwhile investment for the time they save. However, the LED curing light does not have a bulb. Therefore, there is no potential for a loss of intensity in light output with time nor is there a requirement for periodic replacement. Reduced running costs and improved reliability could make it cost effective even though the initial capital cost is greater.

The site of failure for all of these specimens was predominantly at the bracket/adhesive interface, consistent with the findings in other studies (Bishara *et al.*, 1998; Larmour and Stirrups, 2001). Curing the adhesive with the plasma light resulted in significantly more failures with less adhesive remaining on the tooth surface. This could be due to changed polymerization kinetics (the result of a shorter but more intense light exposure) with a consequent effect on the structure of the polymer and the stress within the adhesive and at the interface. In this group (group 2) there was a greater tendency for failure at other than the bracket/adhesive interface which has the potential to increase the incidence of enamel fracture during debond if the applied force is high. Since enamel is a brittle material, a fracture mechanics approach should be adopted. The combination of directing the fracture pathway along the enamel/adhesive interface, the potential presence of defects in the enamel and a high force (due to an effective bond) will increase the risk of enamel fracture. It has been recommended that the tensile bond stress should not exceed 14.5 MPa if enamel fracture is to be avoided (Bowen and Rodriguez, 1962). There is no equivalent recommendation for an upper shear bond stress limit. In the present research, the stress vector on the adhesive was predominantly shear, as it will be in clinical practice when brackets are debonded. Under this regime a stress greater than 14.5 MPa might be tolerated before enamel fracture. It would be helpful to have a numerical shear bond stress limit to represent the upper limit, with Bowen and Rodriguez's (1962) tensile value as the lower limit. Debonding will always be achieved by a combination of tensile and shear components with a recommended net stress limit between the two extremes of pure shear and pure tension. In the present study a single specimen exceeded the 14.5 MPa tensile stress restriction (15.7 MPa, Orthlux XT™ source) without incidence of enamel fracture. This is consistent with the analysis that the failure pathway can remain within the adhesive/bracket and adhesive/tooth interfaces at such a stress level if the applied stress has a significant shear component. What cannot be determined, however, is the increased risk of enamel fracture at this higher applied force (= 166 N, the applied force that produces the stress of 15.7 MPa).

Conclusions drawn from the results of any properly constructed laboratory investigation will provide a sound basis for the clinical introduction of new products and techniques. However, it is in the nature of a controlled scientific experiment that the number of variables will be minimized through the *ex vivo* design to allow the effect of change to a specific variable to be studied. It is possible to simulate conditions that are close to those in clinical use, but the potential for unrecognized factors to influence the outcome should always be borne in mind (Katona, 1997). The results of this *ex vivo* study show that all three curing lights are equally effective but this would need final confirmation in controlled clinical studies.

Conclusions

1. No difference was found in the debond stress of brackets bonded with Transbond™, cured with any of the light sources tested.
2. Statistically significant differences were observed for ARI scores when the light source was changed. There was no difference between the ARI scores produced by the conventional tungsten-quartz-halogen and LED light sources. However, the distribution of ARI scores differed when the adhesive was cured using the plasma arc light.

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