

Light curing time reduction: *in vitro* evaluation of new intensive light-emitting diode curing units

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SUMMARY The aim of the present *in vitro* study was to establish the minimum necessary curing time to bond stainless steel brackets (Mini Diamond Twin™) using new, intensive, light-emitting diode (LED) curing units. Seventy-five bovine primary incisors were divided into five equal groups. A standard light curing adhesive (Transbond™ XT) was used to bond the stainless steel brackets using different lamps and curing times. Two groups were bonded using an intensive LED curing lamp (Ortholux™ LED) for 5 and 10 seconds. Two more groups were bonded using another intensive LED curing device (Ultra-Lume™ LED 5) also for 5 and 10 seconds. Finally, a high-output halogen lamp (Optilux™ 501) was used for 40 seconds to bond the final group, which served as a positive control. All teeth were fixed in hard acrylic and stored for 24 hours in water at 37°C. Shear bond strength (SBS) was measured using an Instron testing machine. Weibull distribution and analysis of variance were used to test for significant differences.

The SBS values obtained were significantly different between groups ($P < 0.001$). When used for 10 seconds, the intensive LED curing units achieved sufficient SBS, comparable with the control. In contrast, 5 seconds resulted in significantly lower SBS. The adhesive remnant index (ARI) was not significantly affected.

A curing time of 10 seconds was found to be sufficient to bond metallic brackets to incisors using intensive LED curing units. These new, comparatively inexpensive, curing lamps seem to be an advantageous alternative to conventional halogen lamps for bonding orthodontic brackets.

Introduction

Curing dental composites with visible (blue) light was first introduced in the late 1970s (Bassiouny and Grant, 1978). A few years later, visible light curing halogen lamps were used to bond orthodontic attachments (Read, 1984; Tavas and Watts, 1984). Light-cured bonding systems have since become increasingly popular among clinicians because they offer a number of advantages over self-cured adhesives. Brackets can be more accurately placed without the time pressure dictated by the setting characteristics of chemically initiated cure, and the removal of excess material is much easier. However, a polymerization time of at least 20 seconds is necessary in order to achieve sufficient bond strength when bonding brackets with conventional halogen lamps because of their relatively low power density (Wang and Meng, 1992; Oesterle and Shellhart, 2001). This considerable investment of valuable clinical time discourages many clinicians from using light-cured adhesive materials.

A number of light curing systems have recently been proposed in an effort to reduce curing time without compromising bonding efficiency. Argon laser produces a consistent, highly concentrated, collimated light, which can reportedly achieve sufficient bracket bond strength with an exposure time of 10 or even 5 seconds (Weinberger *et al.*, 1997; Lalani *et al.*, 2000). In numerous studies investigating

xenon plasma arc light that has the advantage of a relatively high power density, exposure times from 2 to 9 seconds have been suggested in order to achieve bracket shear bond strengths (SBS) that are equivalent to those obtained with conventional halogen lamps (Pettemerides *et al.*, 2001; Klocke *et al.*, 2003). Although these results are very encouraging, the vast majority of clinicians still use conventional halogen lamps to bond orthodontic attachments. The reason is that argon laser or plasma arc light curing devices are complex and costly as compared with the visible light curing devices commonly in use.

Solid state light-emitting diode (LED) technology has recently been introduced for the polymerization of orthodontic light curing adhesive systems. Previous research has shown that at the same irradiance (light intensity) LEDs perform as well as halogen lights (Mills *et al.*, 1999). The first generation of LED units that were commercially available until recently in orthodontics had lower light intensities compared with halogen lamps. However, various reports have shown that they can be used with the same exposure times to bond orthodontic attachments (Dunn and Taloumis, 2002; Bishara *et al.*, 2003). The use of conventional halogen lamps involves some significant disadvantages. Halogen bulbs found in most light cure units have an effective lifetime of approximately 100 hours (Rueggeberg *et al.*, 1996) and

they undergo a degradation of light output over time, which results in a reduction of their curing efficiency. Several studies have shown that many halogen lamps in clinical use do not produce their optimum output due to a lack of maintenance (Miyazaki *et al.*, 1998; Mitton and Wilson, 2001). Instead of the hot filaments used in halogen bulbs, LEDs are a general source of continuous light with high luminescence efficiency, based on the general properties of a simple twin-element semi-conductor diode encased in a clear epoxy dome that acts as a lens. They have a lifetime of over 10 000 hours with relatively little degradation (Haitz *et al.*, 1995), they require little power to operate, are resistant to shock and vibration, and require no filters to produce blue light (Stahl *et al.*, 2000). All these positive aspects, combined with the fact that they are relatively inexpensive, make them an excellent alternative to conventional halogen lamps.

Recently, a new generation of high-intensity LED units has been introduced onto the market. Their manufacturers claim that they combine all the advantages of their predecessors with a considerable reduction in the exposure time needed to bond orthodontic attachments. However, there is as yet no available information on their *in vitro* or *in vivo* behaviour. The aim of this study was to compare the SBS achieved when using two commercially available intensive LED curing units and a high-power halogen lamp to bond orthodontic brackets.

Material and methods

Material

Seventy-five recently extracted bovine mandibular primary incisors (the animals were 18 months old) were collected, stored in a 0.2 per cent thymol solution and refrigerated for a maximum of 3 months. Previous studies have concluded that bovine primary enamel can be used as a substitute for human samples in adhesion tests because of their similarity in physical properties, composition, and bond strength (Nakamichi *et al.*, 1983; Oesterle *et al.*, 1998). Mandibular incisors were used in this study because of their morphological similarity to human upper incisors.




Only teeth with a normal buccal surface morphology and no caries were included in the investigation. The crowns were separated from the roots, polished with oil- and fluoride-free pumice (Bimsstein Pulver, Prochimie, Avenches, Switzerland) for 15 seconds, and then rinsed with an air-water syringe for another 10 seconds.

Bonding procedure

The buccal enamel surface of each tooth was dried and etched for 30 seconds using a 35 per cent phosphoric acid gel. Each tooth was then rinsed again for 10 seconds and dried with oil-free air for another 5 seconds. The buccal enamel surface was subsequently coated with primer (Transbond XT, 3M Unitek, Monrovia, California, USA) and the teeth were divided randomly into five groups of 15 specimens each. Seventy-five stainless steel twin incisor brackets (Mini Diamond Twin™, Ormco, West Collins Orange, California, USA) were directly bonded using a standard light cure composite (Transbond™ XT). The first two groups were bonded using a new intensive LED curing lamp (Ortholux™ LED, serial no. 939830000092, 3M Unitek) with an exposure time of 5 and 10 seconds. Two more groups were bonded using another intensive LED curing device (Ultra-Lume™ LED 5, serial no. 500545, Ultradent Products Inc., South Jordan, Utah, USA) also for 5 and 10 seconds. The final group of bovine teeth served as a positive control. A high-output halogen light curing lamp (Optilux™ 501, serial no. 53109080, Kerr, West Collins Orange, California, USA) was used for 40 seconds to bond the teeth of this group. Some of the technical characteristics of these curing units are presented in Table 1.

The adhesive was applied to the bracket base and the bracket was firmly pressed onto the flattest area in the middle of the buccal surface. Any excess adhesive was carefully removed with a probe. The exposure time was equally divided between the mesial and distal part of the bracket only for the groups bonded using Optilux 501 and Ortholux LED. Ultra-Lume LED 5 has a large light-guiding tip and it was directed at the centre of the bracket. For all groups, light exposure took place with the light-guiding tip

Table 1 Technical characteristics of the light curing units investigated in this study.

| Curing unit | Type | Light source output | Tip dimensions | Light footprint shape | Light intensity* | Wavelength |
|-------------------|---------|---------------------|--------------------------------|---|-------------------------|------------|
| Optilux™ 501 | Halogen | 80 W | 8 mm (diameter) (turbo tip) |  | >900 mW/cm ² | 400–505 nm |
| Ultra-Lume™ LED 5 | LED | 5 W | 10 × 13 mm |  | >800 mW/cm ² | 375–500 nm |
| Ortholux™ LED | LED | 5 W | 7 mm (diameter) |  | 1000 mW/cm ² | 430–480 nm |

*According to the manufacturer.
LED, light-emitting diode.

at an angle of 90 degrees to the tooth surface, and as close as possible to the bracket without touching it.

Testing standardization procedure

Each tooth with the bracket already bonded was mounted on a rectangular acrylic block (Technovit 4071, Heraeus Kulzer, Wehrheim, Germany) that fitted exactly into the corresponding part on top of the load cell of the Instron testing machine (Instron Corp., Canton, Massachusetts, USA). It was crucial to ensure that the buccal tooth surface was roughly parallel to and projecting slightly above the acrylic surface (Pettemerides *et al.*, 2001). A special standardization procedure was followed in order to ensure that the bracket base would be parallel to the force direction during SBS testing. A custom-made metallic rectangular blade was fixed with a drop of glue (Cementit White, Merz & Benteli AG, Niederwangen, Switzerland) into the vertical slot of the bracket before pouring the acrylic. This blade was then laid over the mould and was positioned in such a way that the bracket was situated in the middle of the acrylic block with its base parallel to the borders of the block (Staudt *et al.*, 2005).

The embedded teeth were stored for 24 hours at 37°C (Ishikawa *et al.*, 2001; Oesterle and Shellhart, 2001) in water (Fox *et al.*, 1994). The acrylic block was secured in the lower jaw of the testing machine. The shear force was applied by a custom-made jig, which was parallel to the bracket base with its edge parallel to the occlusal border of the bracket base. The samples were stressed in an occlusogingival direction with a crosshead speed of 0.5 mm/minute. The force values recorded at the point of bond failure were measured in Newtons (N) and were subsequently converted to MegaPascals (MPa or N/mm²). The debonded enamel surfaces were examined under a light stereomicroscope at $\times 10$ magnification (Olympus Optical, Hamburg, Germany) to determine the mode of failure. The adhesive remnant index (ARI) was recorded according to the four-point scale introduced by Årtun and Bergland (1984): 0, no adhesive left on the tooth; 1, less than half the adhesive left on the tooth; 2, more than half the adhesive left on the tooth;

3, all the adhesive left on the tooth with a distinct impression of the bracket mesh.

Statistical analysis

All data are represented as means \pm standard deviations. One-way analysis of variance (ANOVA) was applied in order to detect any differences between groups. The least significant difference test was employed to perform *post hoc* comparisons between groups, and Duncan's multiple range test was used to classify groups into homogeneous subsets. A Weibull analysis was also carried out in order to plot survival probability curves for each group. The ARI scores were compared using the non-parametric Kruskal–Wallis test. All statistical analyses were performed using the SPSS statistical package (SPSS 11.5, SPSS, Chicago, Illinois, USA). A result was considered statistically significant at $P < 0.05$.

Results

The SBS values recorded were significantly different between groups ($P < 0.001$; Table 2). Optilux 501 with an exposure time of 40 seconds recorded the highest mean bond strength (19.2 ± 6.8 MPa), while Ultra-Lume LED 5 and Ortholux LED recorded the lowest (9.5 ± 4.3 and 11.3 ± 4.9 MPa, respectively) when used for 5 seconds only. The *post hoc* comparison revealed the existence of two significantly homogeneous subgroups. The use of both intensive LED devices with an exposure time of 5 seconds led to significantly inferior SBS values. On the other hand, an exposure time of 10 seconds led to bond strength values comparable with those obtained using the halogen lamp for 40 seconds, although the latter exhibited somewhat higher resistance to failure. Applying the Weibull distribution to the data it was possible to plot the bracket survival probability curves for each experimental group (Figure 1). A shear stress of 7.5 MPa, for example, is estimated to produce a bond failure percentage of 5 per cent for Optilux 501, 8 and 12 per cent for Ortholux LED and Ultra-Lume LED 5, respectively, when used for 10 seconds, but more than 25 per cent for both intensive LED units with an exposure time of 5 seconds only.

Table 2 Mean values and comparison of shear bond strength values between the experimental groups.

| Group | Mean \pm SD | 95% confidence interval for mean | Homogeneous subsets* |
|------------------------------|---------------------------------|----------------------------------|----------------------|
| Optilux 501, 40 seconds | 19.2 \pm 6.8 ^{d,e} | 15.4–23.0 | A |
| Ultra-Lume LED 5, 10 seconds | 16.3 \pm 7.1 ^{d,e} | 11.8–20.5 | A, B |
| Ortholux LED, 10 seconds | 15.9 \pm 6.6 ^{d,e} | 11.9–19.2 | A, B |
| Ortholux LED, 5 seconds | 11.3 \pm 4.9 ^{a,b,c} | 8.6–14.1 | C |
| Ultra-Lume LED 5, 5 seconds | 9.5 \pm 4.3 ^{a,b,c} | 7.1–11.8 | C |

SD, standard deviation.

*Significant difference between groups ($P < 0.001$); A, B, C group classification into homogeneous subsets.

a, b, c, d, eSignificant difference ($P < 0.05$) from the group Optilux 501, Ultra-Lume LED 5 10 seconds, Ortholux LED 10 seconds, Ortholux LED 5 seconds, and Ultra-Lume LED 5 5 seconds, respectively (*post hoc* comparison).

A microscopic evaluation of the bond failure site showed that the great majority of bond failures occurred at the bracket base–adhesive interface (Table 3). No significant differences were found between the experimental groups. The majority of failures were of a cohesive nature (ARI scores 1 and 2).

Discussion

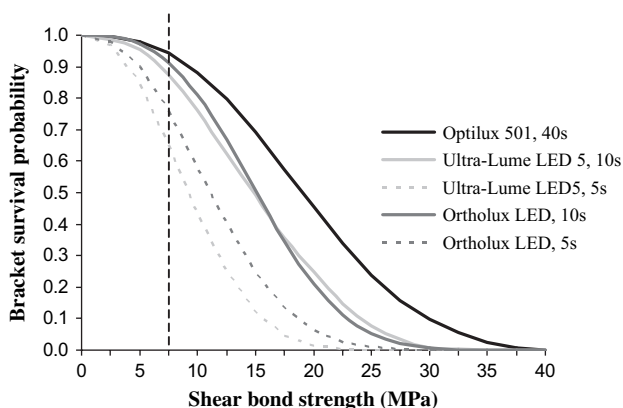
The results of the present study suggest that the new intensive LED curing units may reduce the time necessary to bond orthodontic brackets. An exposure time of 10 seconds achieved SBS values that, *in vitro*, were comparable with those obtained using a high-power halogen lamp for 40 seconds. When the same LED devices were used for only 5 seconds, the resulting bond strength values were significantly lower.

Ultra-Lume LED 5 uses five LEDs (the main diode with a peak wavelength at 450 nm and four additional diodes with a peak wavelength at 400 nm), which are set into a reflector that focuses the light into a high-intensity rectangular

footprint of approximately 10 × 13 mm. Due to the size of the light-guiding tip it is impossible to direct the light only on the mesial or distal half of the tooth. Ortholux LED uses a single intensive blue LED, which produces a bandwidth between 430 and 480 nm with a light intensity of approximately 1000 mW/cm². Its manufacturer recommends an exposure time of 10 seconds (equally divided mesially and distally) when used to bond metallic brackets and only 5 seconds when used to bond ceramic brackets. Optilux 501 is a high-power halogen light curing lamp that yields a light intensity of more than 900 mW/cm² (in boost mode with the turbo tip) (Dunn and Taloumis, 2002; Oberholzer *et al.*, 2003; Kleverlaan and De Gee, 2004). It was used as the positive control, with an exposure time of 40 seconds, in order to compare the new intensive LED units with one of the most powerful conventional halogen-based commercially available devices.

The effective range of the light emission spectrum that can initiate polymerization is narrow. The most common initiator used in visible light-cured adhesives is camphorquinone, which is sensitive to the blue part of the visible light spectrum (360–520 nm), with a peak activity centred around 465 nm (Nomoto, 1997). Halogen lamps produce light when electric current flows through a thin tungsten filament that acts as a resistor. The filament is heated, emitting energy in the form of radiation whose wavelength depends on the temperature reached. High temperatures must be reached in order to achieve visible light emission (Rueggeberg *et al.*, 1996). Preferential production of blue light is impossible and the halogen curing units used in dentistry have special systems to filter out the unwanted portions of the spectrum. As a result, the largest part of the irradiative power is wasted. In contrast, LEDs produce visible light by quantum mechanic effects. A special combination of two different semi-conductors is used to emit a characteristic light with a specific narrow spectral distribution. In other words, LED technology is a more efficient way to convert an electric current into light. LED curing units have been shown to achieve an equal or superior depth of cure in comparison with halogen lamps with approximately the same light intensity when used to polymerize composites (Mills *et al.*, 1999; Jandt *et al.*, 2000).

Reynolds (1975) suggested a minimum ‘clinically acceptable’ bracket bond strength of 6–8 MPa, but the lack of uniformity between bond strength studies (Fox *et al.*, 1994) makes any comparison of strength values between *in vitro* studies practically impossible. The results of the present research confirm the findings of earlier *in vitro* investigations on the previous generation of LED curing devices (Dunn and Taloumis, 2002; Bishara *et al.*, 2003). Although these lamps yielded considerably lower light intensity than halogen-based lamps, which served as controls, they achieved equivalent bracket bond strength values when used for the same exposure times. It should be noted, however, that these values cannot be directly transferred to the clinical



s, exposure in seconds; dotted line, arbitrary shear stress of 7.5 MPa

Figure 1 Survival probability curves plotted for each experimental group using the Weibull distribution. The dotted line corresponds to a mechanical shear stress of 7.5 MPa. The points of intersection on the bracket survival probability curves correspond to the estimated percentage of bond failures.

Table 3 Frequency distribution of the adhesive remnant index (ARI).

| | 0 | 1 | 2 | 3 |
|------------------------------|---|---|----|---|
| Optilux 501, 40 seconds | 0 | 2 | 11 | 2 |
| Ultra-Lume LED 5, 10 seconds | 0 | 3 | 8 | 4 |
| Ortholux LED, 10 seconds | 0 | 1 | 11 | 3 |
| Ortholux LED, 5 seconds | 0 | 0 | 12 | 3 |
| Ultra-Lume LED 5, 5 seconds | 0 | 3 | 9 | 3 |

ARI score: 0, no adhesive remaining on tooth; 1, less than half the adhesive remaining on tooth; 2, more than half the adhesive remaining on tooth; 3, all adhesive remaining on tooth. The Kruskal–Wallis test revealed no statistical difference between groups ($P = 0.86$).

situation where the complex ageing of resin materials in the oral environment and unpredictable stress system generated during mastication play a significant role (Eliades and Brantley, 2000). *In vivo* studies are an indispensable second step to confirm any conclusions drawn in the laboratory.

Conclusions

The results of the present *in vitro* study show that the recently introduced intensive LED curing devices may reduce the exposure time required to efficiently bond orthodontic attachments to only 10 seconds. Compared with halogen lamps, the new LED curing units require 10 times less power to operate, which makes them suitable for portable use in cordless devices. They also have a lifetime of 10 000 hours with relatively little degradation, and are resistant to shock and vibration. The fact that they are also relatively inexpensive makes them an extremely promising alternative for bracket bonding in orthodontics.

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