Effects of time and direction of light exposure on the initial bond strength of orthodontic brackets activated with a high intensity light-emitting diode (LED) source versus a halogen light source

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Effects of Time and Direction of Light Exposure on the Initial Bond Strength of Orthodontic Brackets Activated with a High Intensity Light-emitting Diode (LED) Source versus a Halogen Light Source

A thesis presented by Robert Macdonald
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ABSTRACT

Commercially available high-intensity light-emitting diode (LED) light-curing units recently have been introduced to the dental products market. Few studies have evaluated initial bond strength achieved using manufacturer's recommended cure time and direction of light application. The purpose of this study was to compare the effects of time and direction on the initial shear bond strength of orthodontic brackets cured with a conventional halogen light cure unit (Ortholux XT, 3M Unitek) with a commercially available high intensity LED curing unit (Ortholux LED, 3M Unitek). One hundred forty metal precoated brackets were bonded to extracted premolars. Specimens were divided into 7 groups of 20 teeth each. Groups 1-3 were cured with the conventional halogen light for 20 seconds (10 Mesial(M)/10 Distal(D) – recommended time and direction), 30 seconds (15M/15D), and 30 seconds (10M/10D/10Occlusal), respectively. Groups 4-7 were cured with the LED light for 10 seconds (5M/5D – recommended time and direction), 20 seconds (10M/10D), 20 seconds (5M/5D/10Occl), and 10 seconds (Occlusal only), respectively. All samples were debonded at 5 minutes and tested in a shear mode on an Instron universal testing machine at a crosshead speed of 1mm/min until the brackets debonded. Adhesive remnant index (ARI) scores were determined after failure of brackets. The data was analyzed by two-way analysis of variance and Tukey's multiple comparisons test ($\alpha = .05$). The LED unit produced similar bond strength at its 10 second total recommended time compared to the 20 second total recommended time for the conventional halogen unit ($P = .516$). Bond strength increased using the halogen light as exposure time

increased (P=.003); however, for the LED there was no significant change in bond strength (P=.99) as its exposure time was increased. Adding 10 seconds of light exposure from the occlusal direction in addition to the manufacturer's recommended time of 10 seconds mesial and 10 seconds distal did significantly increase the bracket bond strength using the halogen light but it was no different than curing an additional 5 seconds from the mesial and 5 seconds from the distal (P=.899). Adding 10 seconds of additional light exposure from the occlusal direction did not significantly affect the bond strength using the LED unit (P=.995). However, only applying light from the occlusal surface for 10 seconds with the LED light resulted in significantly lower bond strength values compared to the manufacturer recommendation of 5 seconds from the mesial and distal surfaces (P=.038). A Pearson's correlation analysis of the ARI showed a negative correlation (-.401), or an inverse relationship between ARI and bond strength (as bond strength increased, ARI scores decreased meaning less composite was left on the bonded enamel surface). Within the limits of this study and materials, the results suggest the high intensity Ortholux LED unit can achieve adequate early bond strength using the recommended 10 second exposure time (half the time relative to the QTH), and that additional exposure time does not achieve any subsequent increase in bond strength. Adding exposure time beyond the manufacturer recommended time to the interproximal or occlusal surfaces also does not significantly affect bond strength results with the LED unit used in this study. For cases of bonding second bicuspids, first and second molars, only applying light to the occlusal surface may produce adequate bond strength, though this study showed that the values may be lower than interproximal light applications and additional light exposure from the mesial may be indicated.

INTRODUCTION AND SIGNIFICANCE

It has been known since the 1970's that blue light could be used to polymerize dental composites. Blue light with wavelengths between 410 and 500 nanometers (nm) is of central importance since camphorquinone (CPQ), which is the usual component of photoinitiation systems for dental materials, has its absorption maximum in this range (467nm). When CPQ is exposed to light in the presence of co-initiators (ie. amines), radicals are formed which, in turn, initiate polymerization (Wang and Meng, 1992).

Currently, there are two basic groups that make up the various blue light producing technologies used by the dental community. First are those that produce "white light", which is filtered to the range of blue light, in the 400-500nm range. Lights belonging to this group include the standard halogen (QTH – quartz tungsten halogen) and the plasma arc (PAC) polymerization units. The second group comprises "blue light" curing devices that produce blue light directly. Lights belonging to this group include the laser and light emitting diodes (LEDs).

QTH curing lights utilize a bulb filled with a highly reactive gas (iodine or bromine) and a tungsten filament, that when heated to extreme temperatures of 3000 degrees Celcius by a current results in the production of heat and light energy. The light produced is "white light" which consists of UV, infrared, and visible light wavelengths. A reflector located behind the bulb reflects the light and heat, sending it through two filters: a band pass filter and an infrared filter.

These two filters are often fused together in the manufacturing process. The band pass filter narrows the spectra of white light to the blue wavelength (380 to 520nm) and the infrared filter reduces the infrared spectra and heat passing through to the tooth (Burgess, Walker, Porche, Rappold; 2002). While QTH curing devices have become the clinical standard for light-curing restorative materials, the desire to reduce polymerization times prompted the development of PAC curing lights.

PAC lights use a bulb that contains xenon gas, two electrodes, and no filament. Started by a high voltage pulse, extremely high current densities generate a hot plasma of several thousand degrees celcius. This plasma irradiates light with a spectra that is very similar to that of halogen. The same type of filters are used to produce the blue light and reduce heat (Althoff and Hartung; 2000).

The irradiance levels of the QTH and PAC light sources decline as these units age. In the QTH, this occurs due to the bulb becoming more opaque and the tungsten filament wearing out (eventually burning out completely). Studies indicate these bulbs have a life expectancy between 50 and 100 hours, and recommend replacement every 6 months (Rueggeberg, Twiggs, Caughman, Khajotia; 1996). In PAC, the output is reduced over time by silver being deposited on the lamp due to the high intensity of the lamp (Burgess et al., 2002). Also, the reflectors surrounding the bulbs can degenerate and reduce output. The main problem with this reflector degeneration is that studies have shown that most offices do not routinely service their curing lights, resulting in diminished output and incomplete polymerization of cured composites (Barghi, Berry, Hatton;

1994). The heat emission from these units is another potential problem encountered clinically that can cause problems for the dental pulp (Nomoto, McCabe, Hirano; 2004). For these reasons, researchers began work to develop high-power curing devices that produced light exclusively in the wavelength needed for polymerization, but without further distribution of heat.

The characteristics of an "optimal light source" were outlined in a paper by Althoff and colleagues (2000). According to the authors, this light source would: (1) convert all the consumed electrical power into light of the desired wavelength; (2) produce less heat with no need of fans for cooling; (3) be more efficient (use less energy; possibly battery powered); (4) be small and wireless; and (5) produce a blue light confined to the optimum value of 470 nm, the activation wavelength of CPQ. Lasers were introduced and seemed to offer an interesting alternative since the peak of emitting light can be set precisely around 467nm. However, the total energy conversion (useable light vs. heat produced) proved very poor (.02%), compared with halogen (.7%) and PAC (.2%).

Commercially available light-emitting diode (LED) light-curing units recently have been introduced to the dental products market and offer some distinct advantages compared to the QTH, PAC, or lasers. This LED technology for dental applications is quite different from the LED technology that has been used for decades as light indicators on consumer products (Althoff et al., 2000). LED lights take advantage of semiconductor technology, specifically two different semiconductors – the 'n-doped' and 'p-doped' semiconductors. N-doped semiconductors have an excess of electrons and p-doped semiconductors have a lack of electrons or 'holes'. When both types of semiconductors are combined and a voltage is applied, electrons from the n-doped and holes from the p-doped elements connect. As a result, a characteristic light with a specific wavelength range is emitted (from 3M Technical Product Profile). Although the irradiance (commonly referred to as 'light intensity') of most first generation LED lights as measured with a conventional radiometer was only about half that of conventional QTH devices the narrow band spectrum (Fig. 10) that yields the wavelength of blue light specific for CPQ activation seemed to make up for the overall lower irradiance (discussed in more detail in the Literature Review). Compared with the halogen units, the new LED sources were able to achieve similar physical properties of composites. These characteristics, combined with their small size, battery operation, improved energy conversion, and long life expectancy (10,000 hours) make LEDs a promising technology for the dental community and deserving of continued research especially as the semiconductor technology continues to expand.

These various curing lights have evolved for dental use following the discovery of the acid-etch technique by Buonocore in 1955, in which the enamel was treated with 85% phosphoric acid to alter its surface and make it more receptive to adhesion (Swift, Perdigao, Heymann; 1995). Following etching, the surface shows a honeycomb appearance when viewed under an electron microscope. The acid attacks the prism cores leading to pores 5-6 μm in diameter and extending to a depth of 5-25μm (Reynolds, 1975). The adhesive extends into the pores; forming an intimate irregular interface termed "resin tags", which form a micromechanical bond with the enamel (Gwinnett and Matsui; 1967). In orthodontics, the adhesive must also flow into the mesh of the bracket pad forming the second interface with a micromechanical bond.

To form these micromechanical bonds within the enamel and bracket pad, the adhesive must go through four stages of polymerization: initiation, propagation, maturation/cross-linking, and termination. Blue light with wavelengths between 410 and 500 nanometers (nm) is of central importance since camphorquinone (CPQ), the usual component of photoinitiation systems for dental materials, has its absorption maximum in this range (467nm). CPQ is activated after being exposed to light in the presence of co-initiators (ie. amines), which then reacts with a monomer (individual components of the adhesive). The monomer contains a very high energy and unstable carbon-carbon double bond that splits when combined with the activated initiator, leaving a carbon-carbon single bond and a free, unpaired electron, called a 'free radical'. This radical is very reactive and quickly bumps into and reacts with a nearby monomer, transferring the electron. This process continues and forms a polymer chain. This type of reaction begins at many sites through the mixture of monomers, so there are numerous polymer chains forming simultaneously. Chain lengthening continues with many more monomers being added at a rapid rate (within a few seconds).

These 'linear' polymers begin to branch/cross-link with each other, however, making a more complex structure. Some monomers have two functional carbon-carbon double bonds per molecule instead of only one, which allows them to react with two monomers forming the basis for covalent cross-linkages between various polymeric chains. Growing chains also become entangled around each other (like a bowl of spaghetti noodles) adding to the strength, stiffness, and stability of a given polymer. The polymerization process is terminated most often by either direct coupling of two free radical chain ends or by the exchange of a hydrogen atom from one growing chain to another. However, the polymerization reaction is never quite completed, with continued maturation and cross-linking within the polymer chains for possibly months following initial polymerization (Ferracane, 2001; Phillips, 2003).

The most important clinical factor in orthodontics is whether the adhesive has reached a level of polymerization that will adequately retain brackets to teeth when orthodontic forces are applied. Adequate polymerization of the resin will also help prevent enamel demineralization from occurring under the bracket pads (James, Miller, English, Tadlock, Buschang, 2003). However, no available research has demonstrated the initial bond strength of adhesives in orthodontic systems when using high intensity LED curing lights at the recommended cure times from the manufacturer. Also, effects of increasing cure time and altering the direction of light application on the early bond strength of orthodontic brackets has not been well established.

LITERATURE REVIEW

In recent years, polymerization of dental adhesives using light-emitting diode (LED) technology has become a field of intensive scientific research, commercial product development, and marketing. Research has focused on the two key attributes of all dental curing lights – wavelength of light and light irradiance. It is important to have sufficient total energy (product of light irradiance and duration of exposure) at the correct wavelengths to successfully polymerize composites. Most studies have been in the area of restorative dentistry, comparing LED light sources with quartz-tungsten halogen (QTH) sources by photoactivating dental composites and evaluating the resulting physical properties: surface hardness, compressive strength, flexural strength, depth of cure, and degree of monomer conversion. A small number of studies have been specific to evaluating light sources used to bond orthodontic brackets to teeth.

The early LED sources investigated were relatively weak with respect to irradiance. Light irradiance is usually measured in milliwatts per centimeter squared (mW/cm^2). In 1998, for example, an LED source consisting of 61 individual blue LEDs produced an irradiance value of 100 mW/cm^2 (Fujibayashi, Ishimaru, Takahashi, Kohno, 1998). This experimental LED source produced a depth of cure and a degree of monomer conversion that was significantly greater than that obtained with a halogen source, even though the halogen source was adjusted to give the same irradiance of 100 mW/cm^2. This level of irradiance is about one fifth that of most halogen light-curing units and appeared to limit the range of clinical applications for the LED sources.

As LED technology improved, irradiance values continued to increase. To compare the depths of cure of dental composites, Mills, Jandt, and Ashworth (1999) tested an experimental LED unit containing 25 blue LEDs with an irradiance of 290 mW/cm^2 and a conventional QTH that was adjusted to an irradiance of 300 mW/cm^2. Under these conditions of nearly identical light intensities, the LED source obtained a statistically significant greater depth of cure for three differently filled medium shade composites than did the QTH unit. In 2000, these same researchers tested another experimental LED containing 27 LEDs and an even higher irradiance value (350 mW/cm^2) against a standard QTH with an irradiance value of 755 mW/cm^2 (Jandt, Mills, Blackwell, Ashworth, 2000). They measured depth of cure and compressive strength for ten composite samples of various shades that were 4 mm in diameter and 8 mm in depth. Even with the disparity of the irradiance values, it was shown that there was no statistically significant difference in the compressive strength of composites cured with either LCU. Both units cured the composite deeper than required by both ISO 4049 (industry standard) and the manufacturer. However, the halogen light source did achieve slightly higher and statistically significant values for depth of cure (6.40 mm, Shade A2; 5.19 mm, Shade A4) than did the LED (5.33 mm, Shade A2; 4.27 mm, Shade A4).

In another study, these researchers used these same lights to show that there was no statistically significant difference in the flexural strength and modulus of different composites when polymerized with lights of differing irradiance values (Stahl, Ashworth, Jandt, Mills, 2000). These studies demonstrated that the LED unit performs as well as the QTH source when irradiance values were similar or lower for the LED. Stahl and his associates (2003) offer an explanation for this phenomenon by referencing the specific nature of the wavelength of blue light emitted from the LED units. Figure 10 shows a narrower peak for the LED source with 95% of the wavelengths concentrated between 438 and 501 nanometers (nm), with a maximum spectral irradiance of 465 nm. In contrast, the QTH units produce a broad spectrum band between 398 and 507 nm, with a maximum spectral irradiance at 497 nm. In the region between 450 and 470 nm, the emission of the LED is almost twice that of the QTH. The absorption peak of camphorquinone is 467 nm, which approximately coincides with the emission peak of the LED at 465 nm (Stahl et al., 2000). So although the total irradiance for all wavelengths was lower with the LED than the QTH in these early studies, the wavelengths that overlap the absorbance spectra for CPQ has higher spectral irradiance. The CPQ molecule is activated by absorbing a photon of light energy and becomes a radical that continues to react with the double bonds of the monomers, creating a cross-linked, three-dimensional network of polymers. Activation of the CPQ is more efficient the closer the photon energy (wavelength) matches the needed activation energy (Althoff et al., 2000). Other studies have similarly found that the energy required to generate a given amount of CPQ radicals using the LED units was smaller than that using the halogen units, suggesting that LED light performs better than conventional halogen light with respect to light energy (Teshima, Nomura, Tanaka, Urabe, Okazaki, Nahara, 2003; Nomura, Teshima, Tanaka, Yoshida, Nahara, Okazaki, 2002). A study by

Nomura and associates (2002) also showed that composites cured with LEDs have a higher degree of polymerization and more stable three-dimensional polymer structures than those cured with halogen lights.

While the studies described above demonstrated the positive effects of the LEDs wavelength specificity for the absorption spectrum of the CPQ photoinitiator, more recent studies have been able to show the effect of light irradiance on the physical properties of composites. High intensity LED LCUs have been made possible with LED technology improving to the point of equaling many high intensity halogen LCUs. In 2002, a group of researchers were able to test two high intensity LED prototypes (LED1 – 561 mW/cm^2; LED2 – 831 mW/cm^2), a commercially available LED (LuxoMax – 122 mW/cm^2), and a control QTH (532 mW/cm^2) (Mills, Uhl, Blackwell, Jandt, 2002). Dental composites were cured for 20 or 40 seconds and were tested for Barcol hardness as a function of depth and compressive strength. The two prototype LEDs and the halogen showed similar and satisfactory hardness-depth performances (defined as exhibiting a hardness that was equal to or greater than 90% of the mean hardness of all hardness values obtained at the samples' surface, allowing for a 95% Confidence Interval). The hardness of composites cured with the commercial LED was found to rapidly decrease with increased sample depth and reduced polymerization time (20 sec.). The two LED prototypes also had similar results for compressive strength, whereas the commercial LED exhibited lower overall compressive strength compared to the QTH light. The difference was statistically significant.

More recently, Price, Felix, and Andreou (2003) compared a second generation LED (UltraLume) with a conventional QTH (Optilux) to determine which was better at polymerizing a variety of resin composites. Both LCUs had similar irradiance values of around 700 mW/cm². The LED was used for 20 or 40 seconds to cure 1.6 mm of composite. The Knoop hardness was measured at 15 minutes and 24 hours after curing. When used for 20 seconds, they found that five of the 10 composites were cured as effectively with the LED light as the QTH light, and at 40 seconds this improved to six of the 10. Although there were hardness differences with the two light sources, all 10 composites in the 40 second group cured with the LED light had reached an "acceptable hardness" (greater than 80% of the hardness achieved with the QTH curing light). In these and other studies, the top surface was not as susceptible to variations in light intensities as was the bottom surface (Soh, Yap, Siow, 2003). For example, inferior curing units polymerize the surface just as effectively as properly functioning light sources (Hansen and Asmussen, 1993

To explain the effects of varying light irradiance, it has been shown that as light passes through the bulk of the restorative material, its intensity is greatly decreased due to light absorption and scattering by resin composites, thus decreasing the potential for cure (Ruyter and Oysaed, 1982). Therefore, irradiance of the light source becomes the more critical factor in determining the effectiveness of polymerization at the bottom surface. In the study by Leonard and colleagues (2002), the curing efficiency of three commercially available 1st generation LED sources (LumaCure1 – 173 mW/cm²; VersaLux – 122 mW/cm², ZAP – 32 mW/cm^2) and a conventional QTH source (Optilux 401 – 1080 mW/cm^2) were tested by analyzing the bottom/top Knoop hardness of the polymerized composites. They found that although the emission spectra of the LED sources more closely mirrored the absorption spectrum of CPQ, the overall irradiance was too low to be able to adequately cure the bottom surface of 2 mm thick hybrid and microfilled composites relative to that accomplished by the QTH. They found the LED sources generally required a 2-3 times longer duration of cure. These studies emphasize the importance of having adequate irradiance values.

Conversely, a study of high intensity halogen units with similar irradiance values (>1500 mW/cm^2) showed that greater depth of cure/hardness were achieved with lower cure times compared to that obtained by a conventional halogen source (Kauppi, Combe, 2003). Curing a thin layer of adhesive under metal orthodontic brackets or through ceramic orthodontic brackets is similar to curing composites of greater thicknesses. The light must be able to penetrate to the composite at the deepest levels under the pads in order to gain adequate bond strength to withstand normal orthodontic forces, which are thought to be in the range of 3 to 7.8 MPa (Newman, 1964; Miura, Nakagawa, and Masuhara, 1971; Reynolds, 1975). Three studies have been published dealing with this clinical application.

Dunn and Taloumis (2002) compared bond strengths of metal brackets bonded to extracted human third molars using two halogen based lights (Optilux 501 - 1030 mW/cm^2 and Prolite – 400 mW/cm^2) and two LED lights (Lumacure – 150 mW/cm² and VersaLux – 150 mW/cm²). They had four groups of 25 teeth each, used 40 second cure times and stored the teeth for 24 hours before testing the shear bond strength. Results showed no significant differences among the four groups in bond strength or adhesive remnant index (ARI) scores. The authors concluded that the LEDs could produce similar bond strength values as the conventional QTH lights when used for 40 seconds. This study shows that the LED sources can obtain similar bond strength to the conventional and high intensity halogen units even though they are operating at lower irradiance values, but it is not clear whether this is a function of exposure time and/or wavelength specificity.

The effects of increased light irradiance values of LED lights on orthodontic bond strength was demonstrated by Swanson, Dunn, Childers, and Taloumis (2004). They compared three commercially available LEDs (GC e-light, Elipar Freelight 1st generation, UltraLume LED2) and 1 halogen control (Ortholux XT) by bonding 240 brackets to extracted molars. Irradiance values were not reported in the paper, however, according to the manufacturers, the GC e-light and Elipar Freelight LEDs are each around 400 mW/cm², the UltraLume at 700 mW/cm², and the halogen unit is reported to be 550 mW/cm². Twelve groups of 20 teeth were cured for 10, 20, or 40 seconds, stored for 24 hours, and then tested for shear bond strength. Results showed most groups had mean shear bond strength values ranging from 12.3 to 18.6 MPa, with higher bond strength achieved with increasing exposure time. Higher irradiance values for the LED sources (in addition to the specific, narrow light spectrum) made it possible to achieve similar bond strength in less time compared to the QTH control.

Similar results were reported by Usumez , Buyukyilmaz, and Karaman(2004) when they compared a conventional halogen unit (XL3000, 3M) with a first generation commercial LED unit (Elipar Freelight1, 3M ESPE). This LED light was first produced for general dentistry applications and exhibits lower irradiance (400 mW/cm^2) and "ramped" curing (light becomes more intense as cure time increases) as opposed to the second generation Ortholux LED (3M Unitek) produced for orthodontic applications with a constant irradiance value of 1000 mW/cm^2. Human premolars were used in this study. Four groups of 20 teeth each were cured for 40 seconds with the QTH, and 10, 20, or 40 seconds with the LED before being tested for shear bond strength. They found that the LED when used for either 20 or 40 seconds achieved bond strength that was similar to those achieved with the QTH for 40 seconds (13.1 MPa (QTH) vs. 13.9 MPa (LED)). However, when the LED was used to cure brackets by following the manufacturer's recommended 10 second exposure time, mean bond strength was significantly reduced (9.1 MPa), although this result was still higher than range that is often cited in bond strength studies (3 to 7.8MPa) as being the amount necessary to withstand orthodontic forces. This study did show that this LED light benefited from longer exposure times to achieve higher resultant bond strength, which is probably a function of its average irradiance.

These orthodontic studies were testing the bond strength after 24 hours from initial light activation. Fox, McCabe, and Buckley (1994) discuss the limitations of testing at 24 hours in that many brackets "in vivo" are engaged with archwires and have force placed on them within a few minutes of bonding. Thus, it is important for orthodontists to know what the bond strengths are likely to be soon after curing. Tavas and Watts (1984) concluded that bond strengths increase from 5 minutes to 24 hours, the 5 minute values being about 60-70% of the final 24 hour values; another study reported this percentage at 75% after five minutes (Evans, Peters, Flickinger, Taloumis, Dunn, 2002). Greenlaw, Way, and Galil (1989) found that the bond strength of a visible light-cured adhesive was insufficient after initial curing (initial 1 hour bond strength was only 26% of the 30 hour bond strength) and the authors suggested that the low strength was due to incomplete polymerization. They recommended delaying archwire insertion for 24 hours. Helvatjoglou, Papadigianis, and Koliniotou (1991) reported a continued hardening (progressive cross-linking or polymerization) of both light-cured and chemically cured composite adhesives over a time span of 10 minutes to 12 months. It is interesting to note in the above mentioned studies that 24 hour bond strength did increase as cure times were increased, implying that the initial bond strength may also have been higher in the samples with increased cure time.

The effect of curing time with the latest high intensity LED LCUs on the market and clinically relevant setting times on achieved bond strength is unclear. As mentioned, the setting times measured in the orthodontic studies reviewed above are not practical for routine clinical orthodontics. There is also some question as to which direction of light application produces the greatest bond strength – both initially and at 24 hours. A university study provided evidence that light curing from the occlusal and gingival produced greater bond strength than did light curing from the mesial and distal when using a QTH LCU (Allen, 1996). Altering the direction of cure to the occlusal or cervical regions may increase the amount of light that is reflected through the enamel to the adhesive under the bracket pad, thus affecting bond strength (Eliades T, Johnston, Eliades G; 1995). It is possible that curing down the long axis of the tooth as close as possible to the adhesive/pad interface most efficiently reflects the curing light through the enamel to the resin (Gange, 1995). Gange also recommends that following light exposure from the occlusal direction, additional cure time from either the mesial, the distal, or the gingival margin should be done to maximize polymerization.

Other studies have advocated directing the light through the tooth from the lingual surface to the composite material under the bracket pad on the opposite side of the tooth. This concept, termed transillumination, has been recommended for situations when metal covers the majority of the composite material on the tooth, such as in cases of bonded fixed partial dentures and metal orthodontic brackets (Tavas and Watts, 1979; Oesterle and Shellhart, 2001). While this technique is not commonly used in clinical practice, it does illustrate a fundamental principle of light application to orthodontic adhesives. Both transillumation and traditional curing do not apply light 'directly' to the adhesive under the bracket base. In order for the light to reach the adhesive under the pad, the light must be reflected within the enamel and dentin back to the composite. Additionally, the physical presence of the bracket prevents the light guide tip from being placed directly on the tooth surface, further decreasing the total light energy available to the CPQ activator within the adhesive (light energy decreases by the square of the distance) (Oesterle and Shellhart, 2001). Since the light guide tip can be placed closest to the pad/enamel interface from the occlusal direction and directed down the long axis of the tooth, it could be beneficial to apply light solely or additionally from this direction.

The purpose of the present study was to compare the initial shear bond strength (5 minutes) of the light-activated orthodontic resin under premolar metal orthodontic brackets cured with a conventional halogen light cure unit with the same adhesive/bracket combination cured with a commercially available, high intensity LED light cure unit (when using the factory recommended cure time for each unit). An additional purpose of this study was to determine if bond strength increases as a result of increasing cure time or by altering the direction of cure to the occlusal. After reviewing the available literature, it was hypothesized that the high intensity LED source (1000 mW/cm^2) could effectively polymerize the orthodontic adhesive using a 10 second exposure time (manufacturer recommended time) and obtain adequate bond strength after five minutes from the time of the light exposure, but that these values would be approximately 50% of the 24 hour bond strength values reported in other studies. Further, it was hypothesized that adding additional light exposure time from the mesial and distal, or from the occlusal direction, would have a positive effect on the bond strength of the orthodontic brackets at five minutes following the LED light exposure time.

MATERIALS AND METHODS

One conventional QTH-halogen cure unit (Ortholux XT, 3M Unitek) and one high intensity LED unit (Ortholux LED, 3M Unitek) were chosen for testing (Fig. 1). The Ortholux LED is similar, if not identical, to the Elipar Freelight2 (3M ESPE), which is a second generation LED marketed to general dentists. The Ortholux LED uses a single LED, as opposed to the multiple LEDs (some up to 60+) in many models discussed in the literature review, to produce a high intensity light (1000 mW/cm^2 as reported by the manufacturer) that supposedly does not diminish with the battery output. As long as the battery has life, light output is supposed to be constant. The irradiance of the Ortholux LED unit used in this study was determined by a hand held radiometer to be 825 mW/cm^2. The Ortholux XT halogen light also tested lower (515 mW/cm^2) than the manufacturer reported irradiance (550 mW/cm^2). Both lights were tested initially and after the experiment and demonstrated similar irradiance values for both readings.

One hundred forty extracted human premolars were randomly assigned to 7 groups of 20 teeth each. The criteria for tooth selection included intact buccal and lingual enamel with no visible fracture lines caused by the extraction forceps. Teeth with caries were excluded, while teeth with mild to moderate sized occlusal and interproximal restorations were included. Teeth were stored in distilled water during collection and testing. Sample size was determined by performing a power analysis on the results of a pilot study conducted with the materials and methods described in this paper (α=.05, β=.95, mean Group A – 2.873±1.153 MPa, mean

Group D – 4.512±1.481 MPa; n=5 for each group). The power analysis revealed that a sample size of 17 should show if significant differences between the groups existed. However, a critique of bond strength testing and research performed by Fox and associates (1994) recommended at least 20 specimens be included in each group to test, so the sample size was increased to 20 in each group. The teeth were cleansed of soft tissue and notches were placed in the roots with a high speed handpiece to prevent the teeth from slipping out of rectangular blocks of Triad acrylic (Dentslply Inc., York, PA) while going through the debonding process (Fig. 2). The facial bonding surface was oriented parallel to the front surface of the acrylic block so that after bonding the bracket would be properly positioned for the debonding procedure. Each premolar crown was polished with a mixture of water and fluoride-free pumice using a rubber polishing cup for 10 seconds. The enamel surface was thoroughly rinsed with water to remove any pumice or debris, and dried with an oil-free air stream (each for 10 seconds).

One hundred forty stainless steel universal premolar brackets that were precoated with resin adhesive by the manufacturer (APC, 3M Unitek) were bonded by the same operator to all the teeth. The average surface area of the bracket base was reported by the manufacturer to be 12.9032mm^2. Effort was made to closely simulate a clinical bonding situation. A stone model was poured using a rubber mold of a mandibular arch with a first premolar tooth inserted into the #21 spot, thereby securing this tooth in the model. A bracket was bonded onto this tooth. The stone was hollowed out distal to #21 so that a second premolar and molar could be manipulated such that each premolar sample to be bonded could be placed in close approximation with the adjacent teeth for the bonding procedure Fig. 3). A band was cemented on the molar, which was inserted into an acrylic block of the same height as each premolar block. The premolar teeth to be bonded and the banded molar were placed into the remaining area in the model and secured with Play-Doh (Playskool, Inc., Pawtucket, RI). This allowed manipulation of the teeth so that the interproximal space between the teeth could be closed as much as possible in each individual trial. It was felt that this created a more clinically realistic bonding procedure. Also, effort was made to standardize both the angle of the light cure tip in relation to the premolar to be bonded, as well as the distance from the light source tip to the bracket/tooth interface (measured to be approximately 3mm mesial and distal). This was accomplished by contouring the mesial surface of the molar band bracket to conform with the curvature of the light source tip, so that the light source could be returned to the same position for each test. Additionally, Transbond composite (3M Unitek) was used to make a light guide or support by adapting it around the properly positioned light tip and securing it to the band on the molar and the bracket on the fixed premolar (Fig. 5,6). The distal wings of the bracket were removed so that the composite comprising the guide would not adversely affect the distance from the light tip to the tooth/bracket interface.

Bonding

After initial prophylaxis, the bonding procedure for each bracket followed the manufacturers' guidelines. The enamel surfaces were etched with 37% phosphoric acid gel for 30 seconds, followed by thorough washing (20 sec) and drying (20 sec). In all cases that were etched, the frosty white appearance of etched enamel was observed. After application of the primer on the tooth, the brackets were bonded near the center of the facial surface/height of contour of the tooth with sufficient pressure to express excess adhesive. The excess adhesive was removed from the margins of the bracket base with an explorer before polymerization. The curing protocol for the brackets, for both time and direction, are listed below:

Group 1: QTH light, 20 seconds total (10 Mesial, 10 Distal – manufacturer recommended time)
Group 2: QTH light, 30 seconds total (15 Mesial, 15 Distal)
Group 3: QTH light, 30 seconds total (10 Mesial, 10 Distal, 10 Occlusal)

Group 4: LED light, 10 seconds total (5 Mesial, 5 Distal – manufacturer recommended time)
Group 5: LED light, 20 seconds total (10 Mesial, 10 Distal)
Group 6: LED light, 20 seconds total (5 Mesial, 5 Distal, 10 Occlusal)
Group 7: LED light, 10 seconds total from the Occlusal only

Testing

All groups were debonded at 5 minutes. Each bracket was tested in a shear mode on an Instron universal testing machine, which was calibrated before each session by the same laboratory technician (L.F.). For shear testing, the specimens were secured in the lower jaw of the machine, so that the bracket base of the sample was parallel to the direction of the shear force. A specially designed fixture was secured over the bracket, engaging underneath the gingival wings, and attached to the Instron machine via a chain to allow for slight variations in position of brackets from sample to sample (Fig. 7). The specimens were stressed in an occlusogingival direction with a crosshead speed of 1mm/min (0.05 inches/minute), as recommended by previous studies (Dunn, Taloumis, 2002; Oesterle, Messersmith, Devine, Ness, 1995). The force applied to debond each bracket was recorded in pounds after evaluating the load-deflection curves for the point of complete failure of the adhesive (the peak of each curve) (Fig. 8). The recorded force level was converted from pounds to MegaPascals using the formula: recorded lbs/2.2 = (# of kilograms (kg) X 9.80665) ÷ Bracket surface area = # of MPa (Force/Surface area). The bracket bases and the enamel surfaces were then examined by the same operator under a light stereomicroscope (Nikon SMZ-10) to assess the amount and location of composite remaining on the tooth and bracket according to the adhesive remnant index (ARI), as established by Artun and Berglund (1984).

Statistical Analysis

Descriptive statistics including the mean, standard deviation, median, minimum, and maximum values were calculated for each of the seven groups tested. A two-way analysis of variance was used to identify significant differences in mean shear bond strength with respect to light type, bond time, and direction of cure among the various groups. The Tukey post-hoc test was used to determine which groups were significantly different. Pearson's correlation analysis was performed to analyze relationships between mean shear bond strength and ARI. All statistical analyses were performed at the 0.05 level of significance.

RESULTS

Shear bond strength comparisons

Table I shows the descriptive statistics for the mean shear bond strengths (SBS) of the seven groups tested. Results of the two-way analysis of variance are presented in Table II, followed by results of the Tukey post-hoc test in Table III. ANOVA revealed statistically significant differences among some of the groups tested as related to shear bond strength ($P<.001$). Tukey's test revealed that there was no significant difference in bond strength achieved when using the conventional halogen (Group1 - 6.06±1.39 MPa) and LED units (Group4 - 7.04±1.25 MPa) for the recommended cure times and directions. This test also demonstrated that the bond strength values produced by the conventional halogen source using the recommended cure time and direction (Group1 – 6.06±1.39 MPa) were significantly lower than the bond strength values produced when the cure time was increased by 10 seconds in Group 2 (8.75±1.65 MPa) and also when the cure time was increased by 10 seconds from the occlusal rather than from just the mesial and distal in Group 3 (8.12±2.23 MPa). Conversely, for the LED unit, there was not a significant difference in bond strength achieved when doubling cure time as in Group 5 (7.42 MPa) compared with the bond strength after curing for the recommended time. However, there was no significant difference achieved by altering the direction of cure (or adding cure time from the occlusal) for either light source. Curing with the LED unit only from the occlusal surface showed significantly lower bond strength (5.41±1.40 MPa) when compared with all the groups except for Group 1.

ARI Comparisons

The results of the ARI scores are shown in Table IV. The majority of the ARI scores showed that more than 2/3 of the composite remained on the tooth surface (ie. most of the failures occurred at the adhesive/bracket pad interface). Pearson's correlation coefficient analysis showed a negative correlation between ARI and SBS (-.401) - meaning that as SBS increased, ARI scores decreased (ie. less composite remaining on the tooth).

DISCUSSION

The ability of light-curing units to deliver enough light at appropriate absorption maximum levels for the respective photoinitiator systems is crucial to optimize the physical properties of light-activated dental materials. In orthodontics, the most important clinical factor is whether the adhesive has reached a level of polymerization that will adequately retain brackets to teeth when orthodontic forces are applied. Bond strength values in the range of 3 to 7.8 MPa are generally thought to be able to withstand normal orthodontic forces (Miura et al., 1971; Reynolds, 1975).

Results of the present study indicate that the Ortholux LED unit achieves statistically similar bond strength values to the halogen unit when both are used for the manufacturer recommended exposure times and direction of light application. In addition, ARI scores were comparable for both light units. The fact that the Ortholux LED unit can accomplish this result in half the time can largely be attributed to the high irradiance value of the source. Our results differ from that of Usumez and colleagues (2004) who found significantly lower bond strength of orthodontic brackets cured for 10 seconds with an Elipar Freelight1 LED (3M ESPE) compared with a conventional halogen source; however, the LED had an irradiance value of 400 mW/cm^2 compared to 1000 mW/cm^2 for the LED unit used in this study. The role of irradiance and exposure time as a function of total light energy was discussed in detail by Nomoto (1997). Using a halogen light with constant output, he adjusted the irradiance values by altering the distance of the light tip to the target. He found that the depths of cure and monomer conversion were the same in each of his samples regardless of the light irradiance and duration of exposure, as long as the total amount of exposure was kept constant. When light irradiance increases, the total duration of exposure to achieve similar results can decrease. This finding can account for the difference in what we observed versus that found by Usumez and associates (2004).

While there was no statistically significant difference observed in the bond strength of orthodontic brackets after doubling cure time with the LED unit in this study, bond strength did significantly increase when the halogen unit was used for 10 seconds of additional exposure time over the manufacturer recommendation of 20 seconds total (10 seconds mesial and distal). These results can be explained in part by the light irradiance/duration of exposure relationship noted above, but the difference in the emitted band spectrums of the halogen and LED may also play a significant role. Fujibayashi and associates (1998) demonstrated that the quality of light polymerization is not exclusively due to the light irradiance, but also is related to the absorption spectrum of the initiator system. The blue light emitted by the QTH unit shows a wavelength spectrum between 398 and 507 nm, with a maximum spectral irradiance at 497 nm. The LED unit, on the other hand, emits a narrow wavelength band with 95% of its emissions concentrated between 438 and 501 nm, with a maximum of 465 nm (Stahl et al., 2000; Teshima et al., 2003; Nomura et al., 2004). The absorption curve of the most common photoinitiator, camphorquinone (CPQ), extends between 360 and 520 nm, with its maximum at 465 nm. In the region between 450 and 470 nm, the emission of LED is up to twice that of halogen units, but the halogen exhibits a larger total output in all other spectral regions (represented by the area under each irradiance curve – figure 10). Figure 10 also shows the narrow LED emission spectra is almost exactly located at the maximum of the camphorquinone absorption maximum. This is the reason for the reported higher polymerization efficiency of LED based light sources in comparison to QTH units. When comparing the CPQ absorption spectrum with the emission characteristics of the halogen lights, it can be observed that much of the power at the lower as well as at the higher end of the emission spectrum is not, or only to a very small extent, used for activation of the photoinitiator molecules (Althoff & Hartung, 2000). Further, Nomoto (1997) showed that in the 450-490 nm wavelength range the degree of conversion of monomers within the adhesive is only weakly sensitive to wavelength and the light intensity within this range is more important than the peak wavelength. Outside this range, however, the wavelength dependence is much stronger and the conversion rate drops rapidly. Overall, our results suggest that the LED unit used in the present study emitted a high enough number of photons (irradiance) at the appropriate energy (wavelength) to activate the CPQ and achieve bond strength after 10 seconds of exposure time that was not improved by additional time. The QTH unit was not as efficient since the bond strength improved with times longer than 20 seconds.

While the narrow band spectrum of the LED light is beneficial for adhesives in which CPQ is the main (or only) photoinitiator, composite systems that also use co-initiators can show inferior mechanical properties if polymerized with LED light because the activation energy of these co-initiators often lie outside the emitted band spectrum of LED light, in the <410 nm range. As a consequence, the co-initiator may not contribute to the polymerization processes of the composite (Uhl, Mills, and Jandt, 2002). Since many manufacturers do not reveal the exact composition of their composites, a problem may arise for the practitioner who is unaware that the composite they are using contains such co-initiators that are not activated by the LED light. In this study, the adhesive we used (Transbond XT, 3M Unitek, Monrovia, CA) is a commonly used orthodontic adhesive that does not contain such co-initiators in addition to the main photoinitiator, CPQ. Other adhesives commonly used by orthodontists to bond brackets to teeth should be evaluated further for both composition and activation potential using the latest LED technology.

Adding additional exposure time from the occlusal surface with the QTH and LED resulted in equivalent bond strength to when the light was additionally exposed from the mesial and distal surfaces. This finding has clinical importance because occasionally during bonding procedures access to the second premolars, first molars and second molars (especially the distal surfaces) can be difficult. In such cases, the clinician may have no alternative but to cure from the occlusal surface in addition to the mesial surface. Adequate cure of the adhesive is dependent on the irradiance of the light source, distance from the light curing tip to the bracket/enamel interface, internal light scattering within the composite, and the angle of incidence of the light source (Bayne, Heymann & Swift Jr, 1994; Bennett & Watts, 2004). The present study shows that for such cases, adding light to the occlusal in addition to the proximal surfaces or to the occlusal alone may produce similar and adequate bond strength. Bond strength values achieved by applying light from the LED unit solely to the occlusal surface (5.41 ± 1.40 MPa) were significantly lower than all the other groups, however, this is still within the 'acceptable range' of 3 to 7.8 MPa normally thought to be able to withstand normal orthodontic forces (Newman, 1964; Miura, Nakagawa, and Masuhara, 1971; Reynolds, 1975). This acceptable range of bond strength is oft quoted in orthodontic literature, though there is some question as to how these early suggestions were derived. Reynolds' (1975) article discusses the difficulty of assessing the mean bond strength required of an adhesive because of the wide variability of types/directions of forces applied to an orthodontic attachment – shear, tensile, masticatory, miscellaneous orthodontic forces. He states that some evaluation of the proportion of these forces transmitted to the attachment would be necessary, but doesn't offer suggestions on how this should be done. He does conclude that a maximum value of 60-80 kg/cm^2 (which converts to 6-8 MPa) would "appear reasonable", but offers no clear basis for this conclusion. Studies in publication from that time have adopted Reynolds' early 'suggestion' as the range for acceptable bond strength even though independent studies have not confirmed Reynolds' conclusion. More studies are needed that scientifically evaluate the range of bond strength values required for an adhesive to withstand orthodontic and masticatory forces.

Within in-vitro and particularly in-vivo orthodontic bond strength studies, there are limitations relating to the consistency of the protocol, including variations in distance of the light guide to the enamel/bracket pad interface, individual tooth morphology and subsequent fitting of the bracket pad, and bracket placement pressures that displace excess adhesive, resulting in varying thicknesses of remaining adhesive. The first limitation related to curing light exposure beckons the question: how much light is actually getting to the adhesive? A recent study systematically investigated the relationship between light intensity and distance of the light source tip to the bracket pad/enamel interface (Oyama, Komori, Nakahara, 2004). The investigation measured the irradiance of four commercially available LED units (including the Ortholux LED evaluated in this study), two traditional QTH units, and a high intensity plasma arc unit at distances of zero, five, ten, and twenty millimeters using a radiometer. Both traditional QTH units tested had similar irradiance values to the Ortholux XT QTH used in this study. They found that at 5 mm, the irradiance decreased from 548 mW/cm² to 326 mW/cm² for the similar QTH unit, and from 924 mW/cm² to 368 mW/cm² for the Ortholux LED. As they progressed to a distance of 10, 15, and 20 mm, the irradiance values continued to exponentially decrease. Although the parameters of the present study are quite different than those used to obtain the data in the study by Oyama and associates (2004), it is reasonable to conclude that the irradiance would be reduced under any orthodontic bonding scenario. In the present study, average light source tip-to-bracket pad distance was approximately 4 mm. The fabricated light guides allowed the tips of each light source to be returned to a reproducible position for both mesial and distal curing. Also, this study was conducted by directing the light source tip (on the mesial surface) toward the bracket base at an angle of approximately 60 degrees to the facial surface of the premolar which is likely to have increased the overall irradiance available to activate the adhesive relative to the manufacturer recommendation of activating two brackets at once by holding the light tip parallel to the bracket surfaces and as close as possible without touching them, thus curing the mesial of one bracket and the distal of the adjacent bracket simultaneously. Attempting to partially cure two brackets at one time may further decrease the irradiance resulting in reduced bond strength. Further research should evaluate the results of this manufacturer recommendation.

Other limitations within the present study's protocol included the failure to quantitatively test the light sources throughout the experiment rather than only initially and at the end of the experiment and to randomize the specimens between groups during testing. Each sample group was completed before moving onto the subsequent group. This can introduce potential error and increase variability in the results if, for example, the irradiance fluctuates dramatically from sample to sample or after long-term use. Randomizing the samples reduces this potential for error, or at least spreads the variability to all the groups rather than just one or two. It also limits potential operator bias during testing. After analyzing the data and results, no trends could be established suggesting any introduction of error by not testing the light sources or randomizing the specimens between groups during testing. The results remained consistent between the groups and standard deviations were relatively low. During testing, the LED light was placed onto the charging base between specimens to maintain the batteries. It has been reported by the manufacturer of the Ortholux LED source that the irradiance remains stable over time as long as the battery has sufficient charge. When the battery charge is not sufficient, the semiconductors that make up the LED light source will not be activated (probably a design feature within the circuitry of the unit itself).

All groups in the present study demonstrated adequate bond strength at the five minute debond time. Twenty-four hour bond strength values, as reported by Swanson et al. (2004) using an LED source with lower irradiance, were considerably higher than we obtained. They found the QTH unit, for example, produced mean bond strength of 14.9±5.7 MPa when used for the recommended 20 seconds and the first generation Elipar Freelight LED (400 mW/cm^2) produced a mean bond strength of 13.5±5.1 MPa when used for the recommended 10 seconds, or 14.8±3.2 MPa when used for 20 seconds. The bond strength at 5 minutes post-cure obtained in this study for the same groupings were roughly 50% of these 24 hour values. The increased bond strength at 24 hours is consistent with other studies who reported that bond strengths increase from 5 minutes to 24 hours, the 5 minute values being about 50-70% of the final 24 hour values (Tavas and Watts, 1984; Oesterle et al., 1995). These and other studies suggest that polymerization of light cured adhesives continues long after initial light activation before reaching ultimate bond strength by continuing to harden through progressive cross-linking, especially within the bracket pad mesh (Helvatjoglou et al., 1991; Evans et al., 2002). In clinical orthodontics, the early bond strength just after activation requires the most attention as inadequate strength at wire insertion would result in potential bond failures. Clinicians should also be aware that there is some evidence that in-vivo bond strength values are consistently lower (up to 30% in some cases) than the bond strength values reported in in-vitro research (Murray SD, Hobson RS, 2003).

The ARI scores in the present study indicated that, regardless of the light source, most of the composite remained on the tooth after the brackets were debonded. This type of failure indicates that the weak link in the adhesive chain was between the bracket base and the composite. At five minutes post-cure, the resin penetrating into the undercuts of the bracket base was either not polymerized completely or was still too weak to resist the shear stresses resulting in bond strength values roughly 50% of the potential 24 hour strength values. The bond between etched enamel and composite was generally adequate with any of the light-curing units evaluated, as most of the composite remained on the enamel. Some investigators have concluded that the maturation of the adhesive in the bracket pad undercuts is what is responsible for the increase in bond strength from 5 minutes to 24 hours (Oesterle et al., 1995). However, the ARI scores at 5 minutes in this study are not significantly different from the ARI scores of 24 hour debond studies completed with similar designs and methods (Dunn and Swanson, 2002; Cacciafesta et al., 2002; Usumez et al., 2004; Swanson et al., 2004). This shows that regardless of continuing polymerization, the weak link (at least early on) remains the adhesive/bracket interface. Since it is believed that the polymerization process within the adhesives may continue for months following initial activation through continued cross-linking of polymer chains, future studies may consider evaluating the effects of this continued maturation on the long-term bond strength and ARI scores.

Orthodontists often choose their light source based on effectiveness (achieved bond strength/lack of bond failures) and efficiency (reduced time). This is the reason plasma arc units gained popularity in that they can achieve bond strength in 6 seconds that is comparable to that achieved by a conventional halogen unit in 20 or 40 seconds (Klocke A, Korbmacher H, Huck L, Kahl-Nieke B, 2002). Besides being effective and efficient, LED units have the advantages of being cordless, smaller, and lighter, with estimated lifetimes of over 10,000 hours, and 2 to 3 times less expensive than many plasma arc units. LED sources have been able to take advantage of advances in semiconductor technology to achieve high irradiance values while minimizing heat production, a common problem with the high intensity halogen and plasma arc light sources. The results of this study show a strong future for LEDs in orthodontic practices.

CONCLUSIONS

This study investigated the effects of cure time and direction of light application on the initial (5 minute) bond strength of orthodontic brackets when using a second generation, high-intensity LED unit (Ortholux LED). The results demonstrated that the LED unit produced bond strength values in half the time that were statistically similar to the QTH control when using manufacturer recommended cure times and directions (10 seconds total, mesial and distal for the LED; 20 seconds total, mesial and distal for the QTH). As exposure time increased (from the mesial/distal or occlusal), bond strength also increased for the QTH source, while it remained statistically similar in the groups polymerized with the LED source. Adding additional cure time from the occlusal surface rather than just increasing the cure time from the mesial and distal surfaces did not have any significant effect on bond strength for either light source. However, only curing from the occlusal surface with the LED source produced significantly lower bond strength. There were no significant differences in the ARI scores of any of the groups tested. Most of the remnant composite remained on the etched enamel surface.

TABLES

Table I. Halogen and LED light sources

Light Source	Type	Tip (mm)	Manufacturer	Light Intensity (mW/cm²)
Ortholux XT	Conventional halogen	7.75	3M Unitek, Monrovia, CA	515*
Ortholux LED	Light emitting diode	8	3M Unitek, Monrovia, CA	825*

*Measured with a hand-held digital radiometer prior to and after testing with similar results

Table II. Descriptive Statistics (in MPa) of shear bond strengths of the seven groups tested (n=20).

Group	Mean±SD	Median	Range	Std. Error
1:QTH-20secs total (10M/10D)	6.06±1.39*	6.30	3.11-8.08	.310
2:QTH-30secs total (15M/15D)	8.75±1.65**	8.46	6.39-13.23	.369
3:QTH-30secs total (10M/10D/10Occl)	8.12±2.22	7.51	4.49-13.23	.496
4:LED-10secs total (5M/5D)	7.04±1.25***	6.81	5.77-10.12	.280
5:LED-20secs total (10M/10D)	7.43±1.63	7.06	5.53-11.30	.364
6:LED-20secs total (5M/5D/10Occl)	7.38±1.94	7.06	5.15-14.51	.433
7:LED-10secs total (Occl only)	5.41±1.40****	5.18	3.42-8.39	.313

*Significantly lower bond strength than both Group 2 (P<.001) and Group 3 (P=.003).

**Significantly higher bond strength than Group 1 (P<.001), Group 4 (P=.025), and Group 7 (P<.001).

***No significant differences in bond strength when compared to Group 1 (P=.516), Group 5 (P=.990) and Group 6 (P=.995).

****Significantly lower than all groups except Group 1 (P<.05)

Table III. Results of two-way ANOVA.

		Sum of Squares	dF	Mean Square	F	Sig.
Bond Strength (MPa)	Between Groups	157.143	6	26.191	9.399	.000*
	Within Groups	370.602	133	2.786		
	Total	527.745	139			

*α=.05

Table IV. Frequency distribution of ARI scores of experimental groups.

	ARI scores*				
Group	0	1	2	3	4
1:QTH-20secs total (10M/10D)	0	0	4	13	3
2:QTH-30secs total (15M/15D)	0	4	4	12	0
3:QTH-30secs total (10M/10D/10Occl)	0	2	4	14	0
4:LED-10secs total (5M/5D)	0	1	1	17	1
5:LED-20secs total (10M/10D)	0	4	3	13	0
6:LED-20secs total (5M/5D/10Occl)	0	3	6	11	0
7:LED-10secs total (Occl only)	0	0	0	17	3

* 0, no adhesive remaining on tooth; 1, less than 1/3 adhesive remaining on tooth; 2, 1/3-2/3 adhesive remaining on tooth; 3, greater than 2/3 adhesive remaining on tooth; 4, enamel bonding site covered entirely with adhesive with imprint of bracket pad.

FIGURES

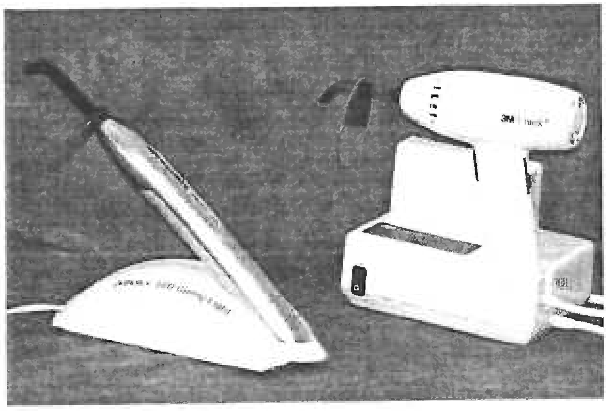

Fig 1. Ortholux LED and Ortholux XT (3M Unitek)

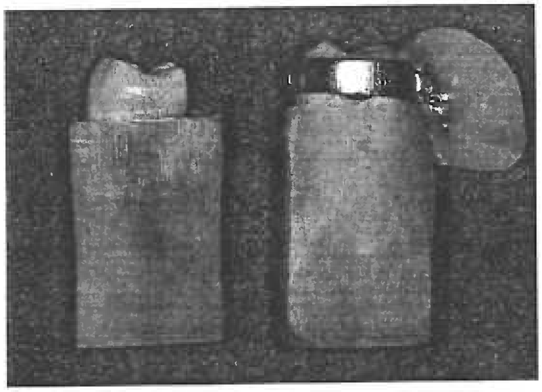

Fig 2. Teeth mounted in acrylic blocks.

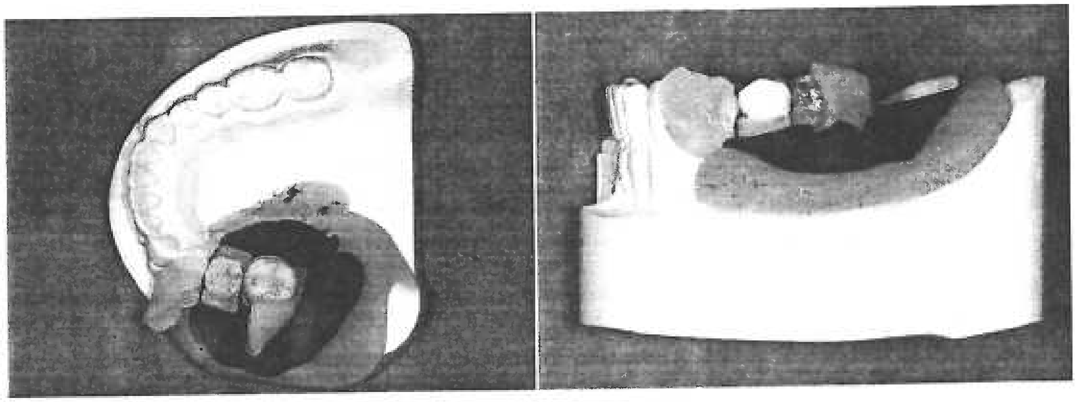

Fig 3. Occlusal and side view of light cure guides and teeth positioned for bonding procedure.

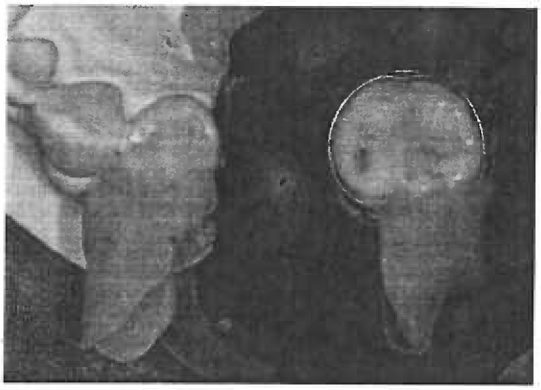

Fig 4. Space for premolar acrylic blocks; close-up of light cure guides.

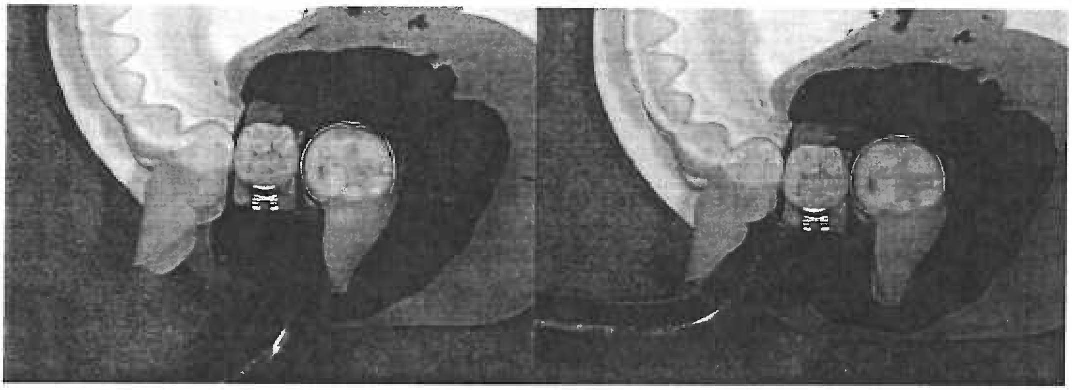

Fig 5. Curing distances and angles of halogen light cure unit.

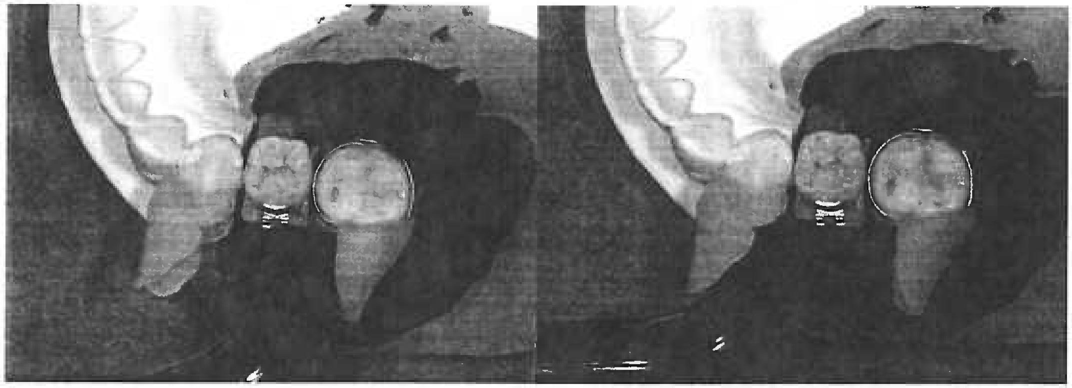

Fig 6. Curing distances and angles of LED light cure unit.

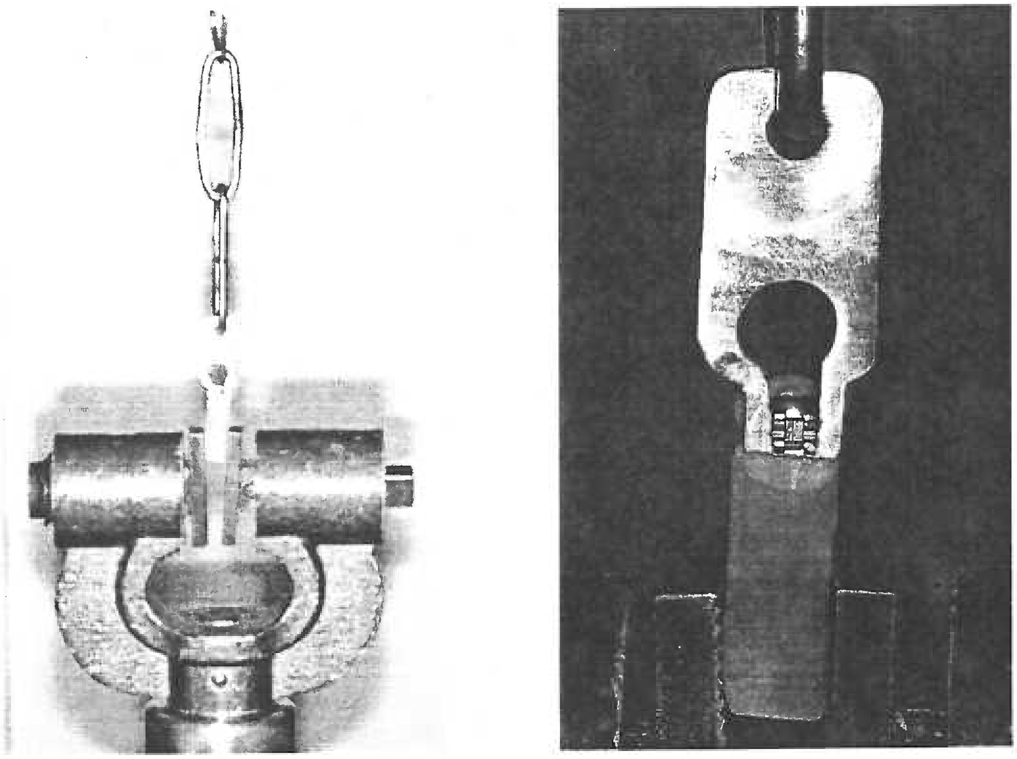

Fig 7. Instron set up and debonding jig

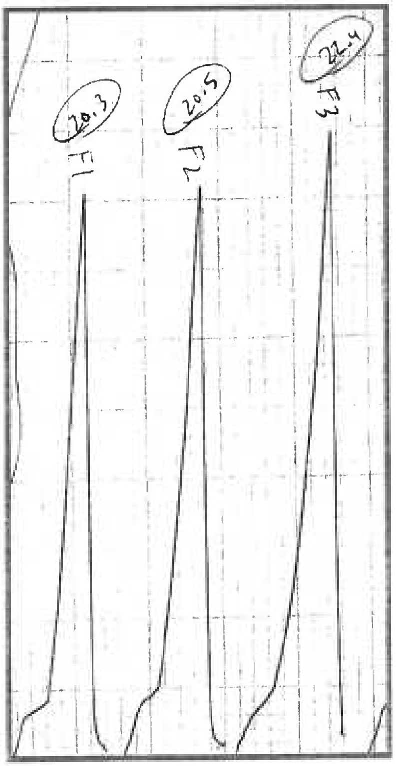

Fig 8. Force/Displacement Curve (recorded in pounds)

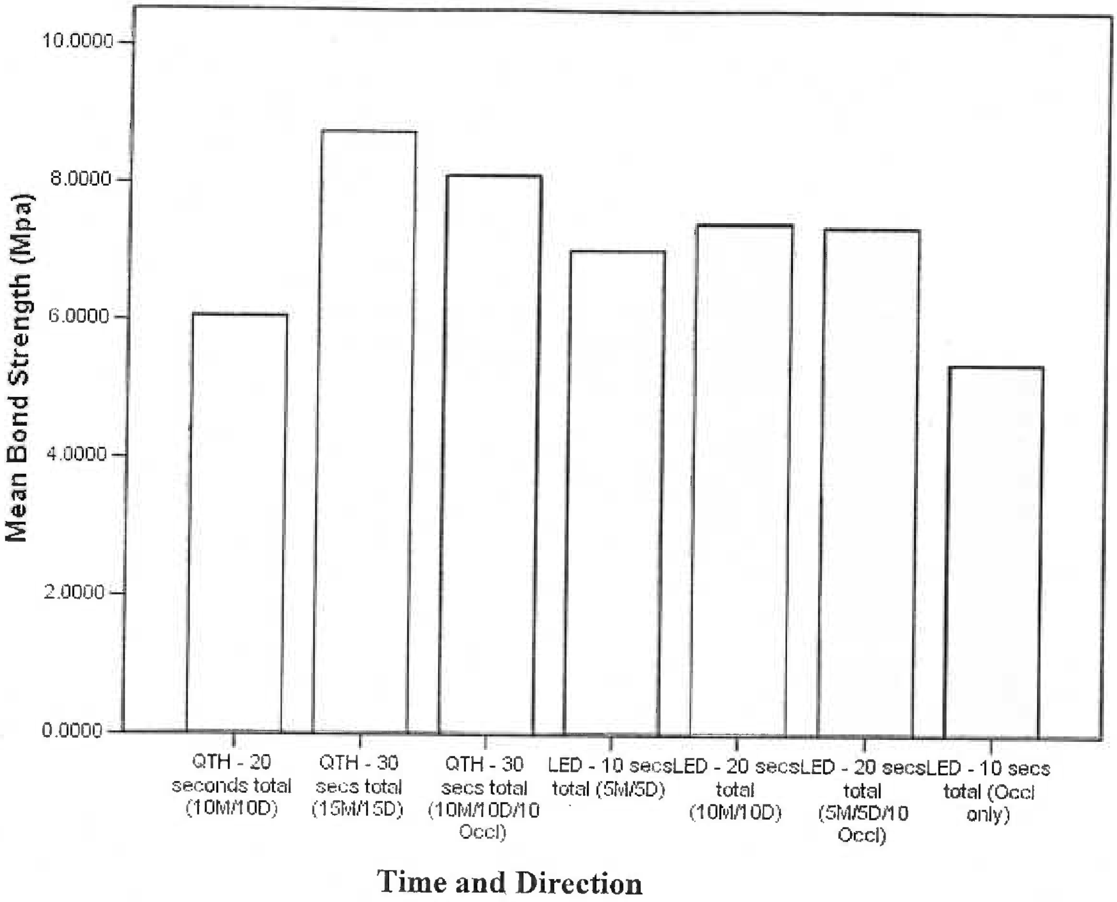

Fig 9. Bond strength graph for Groups 1-7

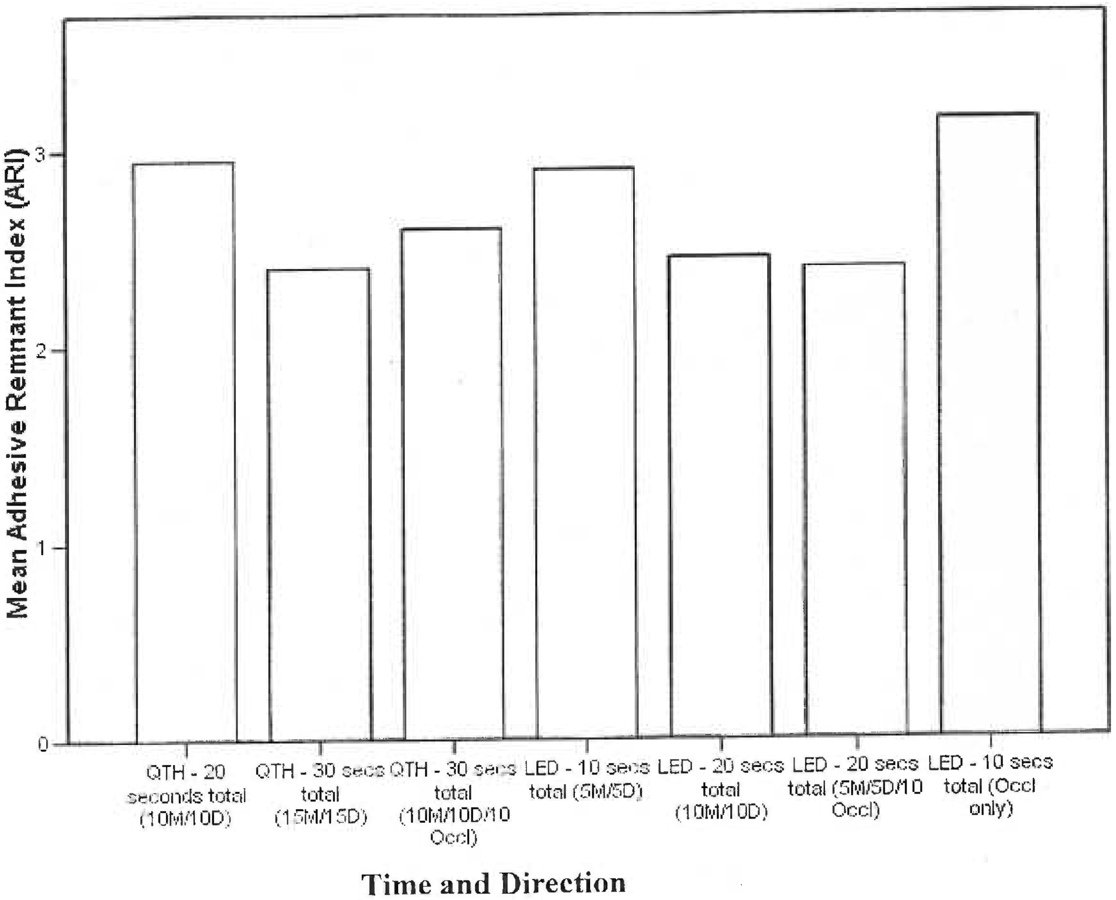

Fig 10. ARI results for Groups 1-7.

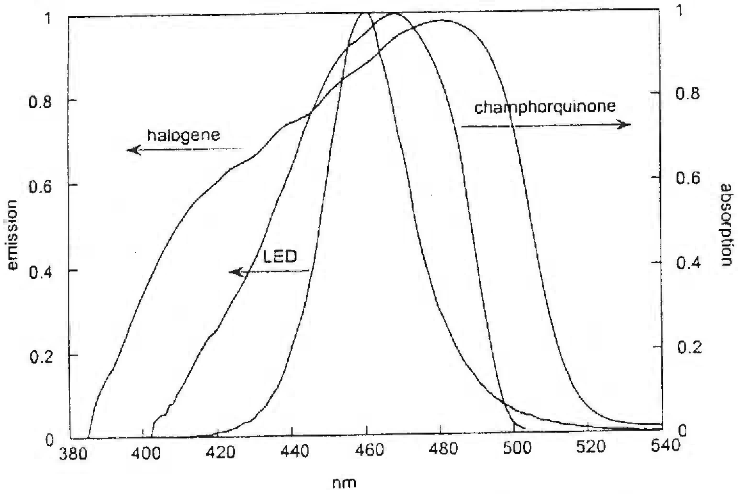

Fig 11. Graph of the emission spectra of an LED and Halogen light source superimposed over the absorption spectrum of camphorquinone.

(From Althoff O., Hartung, M. Advances in light curing. Am J Dent 2000;13(Spec No): 77D-81D.)

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