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New High Intensity Light-Emitting Diode (LED) Curing Lights: An in vitro Evaluation of Increased Power Density at Reduced Curing Times

Jeff Mirrielees
Medical University of South Carolina

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New High Intensity Light-Emitting Diode (LED) Curing Lights: An *in vitro* evaluation of increased power density at reduced curing times

Jeff Mirrielees

A thesis submitted to the faculty of the Medical University of South Carolina in partial fulfillment of the requirement for the degree of Master of Science in Dentistry in the College of Dental Medicine

MUSC College of Dental Medicine
Department of Orthodontics and Pediatric Dentistry

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Approved by:

Dr. Jing Zhou

Dr. Hai Yao

Dr. Ronald Bell

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ABSTRACT

JEFF MIRRIELEES. New High Intensity Light-Emitting Diode (LED) Curing Lights: An *in vitro* evaluation of increased power density at reduced curing times. (Under the direction of Dr. Jing Zhou and Dr. Hai Yao). **Introduction:** The purpose of this study was to evaluate two new light-emitting diode (LED) curing lights with increased power densities at reduced curing times. **Methods:** Ninety extracted bovine incisors were examined in vitro. The incisors were divided into six test groups and metallic adhesive pre-coated brackets were bonded using either the Valo Otho (Opal Orthodontics, Ultradent) @ 3200 mW/cm^2, or the Ortholux Luminous (3M Unitek) @ 1600 mW/cm^2 at curing intervals of 3-, 6-, or 12-seconds. The samples were stored for 24 hours in 37 degree Celsius water and debonded. Brackets were tested using an MTS Mini-Bionix II testing machine at a crosshead speed of .5 mm/minute. The bracket failure interface was analyzed using an adhesive remnant index (ARI) score. Data were analyzed using Shapiro-Wilk tests, two-way ANOVA procedures, and Kruskal Wallis tests (ARI scores). **Results:** No significant differences were found in the mean shear bond strengths produced by each of the curing lights at the different curing times or between the two lights at the same curing times. Mean (±SD) shear bond strengths (MPa) for the Valo Ortho at 12, 6 and 3 seconds were 27.82 ± 7.06, 26.97 ± 4.31, 26.95 ± 6.42, respectively; and for the Ortholux Luminous at 12, 6 and 3 seconds were 28.37 ± 4.92, 25.72 ± 4.98, 24.99 ± 4.92, respectively. In terms of total energy density, the varying power densities at different combinations of curing time did not produce shear bond strengths that were significantly different between any of the test groups. Further, there were no significant differences between ARI scores for each of the LED lights following debonding.

Conclusion: These results indicate that there are no statistically significant differences between the bond strengths produced when using the Valo Ortho (Ultradent) or the Ortholux Luminous (3M Unitek) for 3-, 6-, or 12-seconds. Also, 3 second exposure times produced bond strengths that appeared similar to those produced at 6- and 12-seconds when using either light.

INTRODUCTION

In the modern orthodontic practice, the amount of time spent photo-polymerizing brackets is of critical significance. In terms of practice management, shorter curing intervals would allow for increased patient comfort as well as decreased chair time and a decrease in the susceptibility to contamination. As such, orthodontic practitioners strive for the most efficient and effective systems in terms of protocols for bonding orthodontic brackets using light-cured adhesives.

As a result of technological advances, the output capabilities of light curing units have increased drastically over the past decade. These increases in output—commonly referred to as power density (mW/cm^2)—have resulted in a decrease in the amount of time required to photo-polymerize orthodontic brackets. However, there is conflicting information regarding the clinical benefits of the current trend towards increased power densities at reduced curing times (Mavropolous et al., 2008)

This study will analyze the newest generation of light-emitting diode (LED) curing units. To date, there has been minimal published data on the third generation of LED curing lights with respect to their increased power densities and reduced recommended curing times. The current 'in vitro' study will use bovine incisors to analyze the shear bond strength of brackets photo-polymerized with two state-of-the-art curing lights—Ortholux Luminous (3M Unitek); Valo Ortho (Ultradent)—at 3, 6 and 12 seconds.

The results of this study will provide relevant data on the newest generation of LED curing lights. In addition, valuable information will be obtained regarding the theory of reciprocity between power density and curing time. The specific aims of the current study are as follows:

Specific Aim 1: To analyze potential differences between the shear bond strength of brackets cured at a power density of 3200 mW/cm^2 (Valo Ortho, Ultradent) at varying curing intervals of 12, 6 and 3 seconds.

Specific Aim 2: To analyze potential differences between the shear bond strength of brackets cured at a power density of 1600 mW/cm^2 (Ortholux Luminous, 3M Unitek) at varying curing intervals of 12, 6 and 3 seconds.

Specific Aim 3: To analyze potential differences in the shear bond strength of brackets cured at constant exposure times (12s, 6s, 3s) with varying energy densities using two new LED curing lights; 3200 mW/cm^2 vs 1600 mW/cm^2.

Specific Aim 4: To analyze potential differences in the shear bond strength based on the total energy density (J/cm^2) to which each bracket was exposed based on the product of power density and curing time for each light.

Historical Overview

Prior to the use of bonded orthodontic brackets, circumferential orthodontic bands were required on every tooth during orthodontic treatment. In addition to being uncomfortable for the patient, these bands were time-consuming to install/remove and were less accurate in terms of placement. The introduction of the enamel etching procedure in the late 1960's allowed brackets to be bonded to teeth using auto-cure orthodontic adhesives (Buonocore MG, 1955). Next, the polymerization of composite materials using visible light curing methods became available in the dental market in the late 1970's which quickly gave rise to the use of photo-polymerizing composite adhesives in orthodontics (Bassiouny and Grant, 1978). The two major advantages of using light-cured orthodontic adhesives when compared to the auto-cured method are the longer working time and the ability to cure on demand. Following the introduction of composite light-cured materials 35 years ago, the market for light curing units (LCU's) has continued to evolve as manufacturers and practitioners search for the most efficient light curing units (Pelissier, 2011).

There are four major types of LCU's available on the dental market:

1. Quartz-tungsten halogen (QTH) lamp
2. Xenon plasma lights
3. Argon lasers
4. Light emitting diodes (LED's)

The first LCU to be used for orthodontic bonding was the quartz-tungsten halogen (QTH) lamp introduced in 1984 (Read, 1984). For approximately three decades following its introduction, the QTH lamp was the most common method used for curing light-activated composite materials (Silta et al. 2005). The QTH lamp produces visible light using electrical power to heat a tungsten filament within a bulb. Although the QTH lamp is effective in terms of curing orthodontic brackets, it has numerous reported disadvantages. The method by which the QTH lamp produces light for photo-polymerizing is inefficient because almost 98% of the radiation is lost as heat (Mavropolous et al, 2005). The excessive heat requires a fan for cooling and also results in degradation of the bulbs over time giving the QTH lamp an effective lifetime of 40-100 hours (Palomares et al., 2008). Barghi et al determined that close to 50% of QTH lights that were tested from 122 private offices had power outputs less than the minimum power density that is required to photo-polymerize composite materials, 300 mW/cm^2 (Barghi et al, 1994; Silta et al., 2005). In addition to the short lifespan and degradation of power density, QTH lamps are very sensitive to shock and vibration and they produce a large spectrum of light when compared with the small, usable spectrum of camphorquinone (Silta et al., 2005; Mavropolous et al., 2005). Although there have been improvements to QTH lamps over time, most traditional QTH lamps recommend an exposure time of 40 seconds when photo-polymerizing metals brackets (Swanson et al., 2004).

Xenon plasma arc lights and argon lasers are able to produce high power densities by passing electrical currents through ionzed gas to produce highly concentrated, collimated light in the desired spectrum (Signorelli et al., 2006). These lights have been studied extensively and are suggested to produce shear bond strengths comparable to those of QTH lights in as little as 5 to 10 seconds for argon lasers (Weinberger et al., 1997; Lalani et al., 2000) and as little as 2 to 9 seconds for xenon plasma arc lights (Pettemerides et al., 2001; Klocke et al., 2003). However, argon lasers and xenon plasma arc curing lights have not been widely accepted for use in clinical practice due to their increased complexity, size and cost when compared with other methods (Mavropoulos et al., 2005)

Light-emitting diodes (LEDs) create visible light using chips comprised of a semi-conductor material (usually gallium nitride and indium) which create a complex network of anodes and cathodes separated by gaps. When electrons pass through these gaps, they emit energy in the form of photons (Pelissier, 2011). In 1995, Mills was the first to introduce the LED curing-light into dentistry (Mills et al, 1995). It was believed that the new LED technology overcame many of the disadvantages of traditionally used QTH lamps. Due to their design compared with the design of QTH lamps, LED lights are light-weight, durable (shock-resistant), have reduced heat and noise, smaller size, lower power requirements, long output life of over 10,000 hours (with minimal degradation) and finally, a light emission spectrum centered around the absorption spectrum of camphorquinone (Pinto et al. 2011, Marquezan et al., 2010). With the numerous design benefits offered by LED technology, the only question remaining was in regards to their clinical performance compared to the popular QTH lamps.

With the first generation of LED curing lights there were multiple studies done comparing the shear bond strength of LED lights to the traditional Quartz-Tungsten Halogen lamps. It was reported that due to their specific wavelength which is centered around that of camphorquinone, LED curing lights could achieve an equal or superior depth of cure in comparison with halogen lamps at approximately the same light intensity (Mills et al 1999). This theory seems to have been supported by other bond strength studies where LED curing lights produced SBS values that were similar to QTH lamps when used at the same exposure time with considerably lower power densities (Marvopoulos et al., 2005; Bishara et al., 2003).

Following those initial studies, LED technology continued to improve and the power capabilities of the lights has increased up to 400-600% over the past 10 years. As the power densities continue to increase, the curing intervals continue to decrease suggesting that LED technology is becoming more efficient. More recent publications have advocated shortened curing intervals for LED curing lights compared with the 40 seconds recommended for traditional QTH lamps. Swanson et al., found clinically acceptable SBS at 10 seconds but recommended longer curing times of 20 seconds as in the manufacturer's instructions (Swanson et al., 2004). Other studies suggested that brackets bonded with LED curing lights at 20 seconds were no different that SBS values obtained from traditional QTH lamps at 40 seconds (Usumez et al., 2004; Banerjee, et al., 2011; Swanson et al, 2004). As time passed and LED technology continued to improve, newer LED curing lights were producing acceptable bond strengths at 10 seconds compared with the traditional 40 second QTH cure (Cerekja et al., 2011). As

LED chip technology evolved, power densities of the LED curing lights continued to increase which resulted in the recommendations for even shorter curing intervals.

In 2011, a paper was published in a restorative dentistry journal (Restorative Update) by Bruno Pelissier reviewing the history of LED curing light technology. In this article, three generations of LED curing lights were discussed. The first generation of LED curing lights (1999-2002) were described as having lower power densities and requiring longer polymerization times. The output wavelength of this generation of LED lights was very narrow and was centered around that of camphorquinone (465 nm). An example of a popular first generation LED curing light is the Elipar Freelight by 3M ESPE that had a power density in the range of 250-280 mW/cm^2. Although the power density was less when compared to a QTH lamp, it was mentioned that the Freelight could cure as effectively as a QTH lamp with a power density of 400 mW/cm^2 due to its wavelength spectrum being very similar to that of camphorquinone. However, curing times between 15 and 60 seconds were still needed for the first generation of LED curing lights (Pelissier, 2011).

The second generation of LED curing lights (2002-2004) resulted from improved computer chip technology wherein a smaller chip design was being used so that a much more powerful light-emitting diode could be manufactured. These lights had power densities of up to 1000 mW/cm^2 and could reach curing depths in half of the time compared QTH lights of the same power. Popular LED lights from this generation were the BluePhase from Inovlar Vivadent (Enderby, Leics) and the Elipar Freelight 2 (3M

ESPE). One problem with this generation was the amount of heat that was generated by this increased power which could possibly damage the light-emitting diode with extended use (Pelissier, 2011).

Finally, Plessier described at third generation of LED curing light (2004-2011). These lights are capable of emitting light at power densities even higher than those of the second generation and are able to emit blue light in a "polywave spectra". This means that in addition to emitting light in the 465 nm absorption peak of camphorquinone, they also incorporate multiple LEDs to produce light corresponding to other wavelengths-"polywave"-that can be useful when curing materials with photo-initiators that have absorptive peaks at wavelengths that differ from that of the 465-470 nm for camphorquinone. However, these other photo-initiators often relate to the color changing properties of camphorquinone which are more relevant in the esthetic aspects of restorative dentistry and may not apply as directly to orthodontic adhesives. An example of a third generation "Polywave LED" light is the Valo light from Ultradent with three different LEDs resulting in a very wide range spectrum. In addition to the increased range of light spectra, the third generation LED's have chip technology that allows for power densities known as "high power, turbo or plasma emulation mode" that approach and exceed 3000 mW/cm^2. A new light by Rocky Mountain Orthodontics known as the FlashMax P3 is advertised as the most powerful light on the market in 2012 with a power density of 4000-6000 mW/cm^2. The recommended curing time using the Flashmax P3 is only 3 seconds.

Although the trend for increased power densities and decreased curing times has continued to increase over the past 10 years, one has to wonder if there is an overall limit for clinically useful power density? It has been suggested that composite resins have a maximum polymerization rate and that simple reciprocity does not exist between further increases in power density and reduced curing times (Pelissier, 2011; Mavropolous et al., 2008).

In Vitro Shear Bond Strength Testing

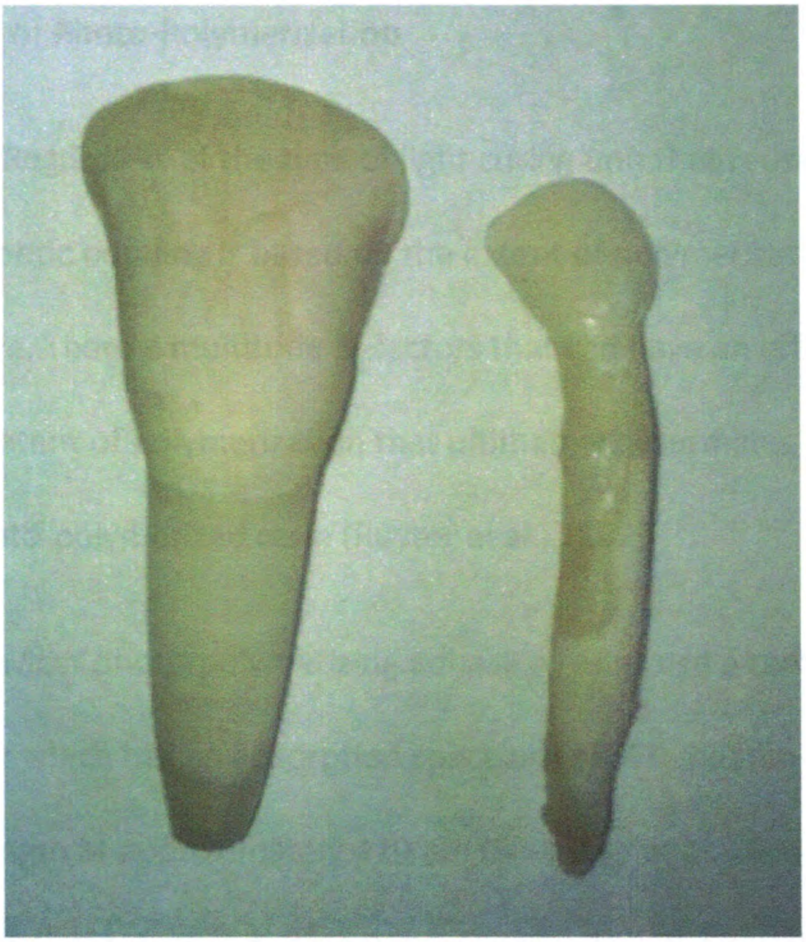
The method of in vitro shear bond strength testing became popular for analyzing the efficiency of different bonding protocols after Zachrisson reported in 1979 that 97% of orthodontists were using the direct bonding technique (Fox et al., 1993). Shear bond strength (SBS) is an engineering term used to describe material failure (or yield) under a shear force. In orthodontic studies, SBS values are obtained in vitro using a machine that quantifies the largest amount of force (Newtons, N) that a bracket can withstand before failing. This value is then divided by the surface area of the bracket in mm^2 which gives the total amount of stress (force/unit area) placed on the bracket prior to failure and is measured in MegaPascals (MPa).

In terms of shear bond strength, the "gold standard" used by numerous studies was published by Reynolds' et al. in 1975 that suggested a clinically acceptable bond strength of approximately 6-8 Mpa (Reynolds et al., 1975; Grandhi et al. 2001; Webster et al.,2001; Zeppieri et al., 2003; Swanson et al., 2004; Fjeld and Ogaard ,2006; Yoshida et al, 2011). Retief et al. reported that enamel fractures can occur with bond strengths as low as 13.5 Mpa and a failure between the bracket base and the adhesive is desirable so that enamel is not damaged in the case of a high bond strength (Retief et al., 1974).

For any in vitro shear bond strength study, it is imperative that the tested enamel surface to which the bracket is bonded is parallel to the shearing force of the testing machine. In essence, the bonded surface of the orthodontic bracket needs to be parallel to the shearing force to decrease variability between test samples. For this reason, the relatively flat facial surface of human maxillary central incisors would be ideal for testing while the overly convex surface of premolars and molars make their use much more complex and variable. Unfortunately, it is difficult to collect large numbers of non-carious human maxillary central incisors. It has been reported that bovine enamel is a reliable substitute for human enamel in bonding studies (Oesterle et al, 1998; Nakamichi et al, 1983). Although the bond strengths to the bovine enamel were slightly lower than that of human enamel, both studies reported that these differences were not statistically significant. In addition, it has also been observed that deciduous bovine incisors had greater bond strengths than their permanent successors so it was imperative that the teeth used in bond strength studies were all deciduous teeth from cattle approximately 18 months of age during the mixed dentition (Oesterle et al, 1998). Figure 1 depicts the ease in distinguishing between primary and permanent lower bovine incisors.

Historically, orthodontic bonding studies have analyzed shear bond strengths at either 30 minutes post-bonding or 24 hours post-bonding. Following the photo-polymerization of orthodontic brackets, numerous previous studies have shown that the bonded orthodontic brackets have an increase in shear bond strength during the first 24 hours (Oesterle et al. 2008; Yamamoto et al., 2006). Oesterle et al. also reported that there is then a trend for the shear bond strength to decrease over the next 24 months. For logistical reasons and to allow for the strongest bond strength potential for the different test groups analyzed in this study, brackets were mounted and then stored in a dark, 37 degree Celsius water bath for 24 hrs before being stressed in the testing machine.

Figure 1: Permanent Vs. Deciduous Bovine Incisor



Physics of Photo-Polymerization

Regardless of the type of light curing unit that is used, the efficiency of orthodontic bonding is based on the extent of polymerization that occurs within the adhesive. There a multitude of factors that can have an effect on polymerization and it is the extent of polymerization that ultimately determines the mechanical properties of the photo-polymerized resin (Ruyter el al., 1982).

Most photo-polymerizing adhesive resins use a camphorquinone as the photo-initiator which has an absorption spectrum of 370-520 nm (blue range) with a peak wavelength of approximately 470 nm (Swanson et al. 2004). Upon activation of the photo-initiator, free radicals are produced within the resin converting the monomer into polymer (polymerization). Thus, it is critical that the light curing unit produces light that overlaps as closely as possible to the specific absorption spectrum of the photo-initiator used in the light-cured resin.

Once the light curing device has been constructed to produce light within the specified output wavelength, the next two critical factors affecting the degree of polymerization are the amount of energy absorbed by the adhesive and the amount of exposure time. Together, these two variables are referred to as "energy density" which is the rate at which light photons reach the surface of the adhesive and the time at which the adhesive is exposed to these photons (Mavropolous, 2008). The degree of polymerization is based light output, composition of the composite and exposure time which ultimately has a direct effect on the mechanical properties of the adhesive (Ruyter et al 1982). Numerous studies have suggested that higher power densities result in more photons reaching the composite which produces more free radicals available for conversion of monomer to polymer (Mills et al, 1999 ; Dunn and Taloumis, 2002). The total amount of energy to which an orthodontic adhesive is exposed can be explained by the following equation relating total energy density, power density and curing time (Mavropolous et al. 2008):

$$\textit{TOTAL ENERGY } (J/cm^2) = \textit{Curing Light Power Density } (mW/cm^2) \;\; X \;\; \textit{Curing time (seconds)}$$

In addition to output wavelength, power density and curing time, there are numerous other variables that may also have an effect on the polymerization of the orthodontic adhesives. Some of these variables are the light to bracket distance, light to bracket angle, light tip diameter, light tip collimation, metal vs. ceramic brackets and the type and amount of adhesive used for bonding. The current study will focus on keeping these factors constant while focusing on power density and curing time.

Light Curing Units

The current study will compare shear bond strengths using metallic orthodontic brackets bonded with two new, state-of-the-art light curing units.

The Ortholux Luminous (3M Unitek) was introduced in the summer of 2009 and has a power density of 1600 mW/cm^2. The power density of the Ortholux Luminous is over 50% stronger than its predecessor, the Ortholux LED (3M Unitek) with a power density of 1000 mW/cm^2. The new light is comprised of the latest LED technology, an 8 mm black, collimated fiber optic light guide tip and a built-in heat sink to manage excess heat produced by the light. The peak wavelength of the Orhtolux Luminous is 455 nm and it has timed settings of 3, 6 and 12 seconds. Preliminary studies done by the manufacturer using bovine incisors found that the Ortholux Luminous produced bond strengths at curing intervals of 3 seconds that were greater than the Ortholux LED at 5 seconds when tested at 24 hrs. Data reported on SBS for the 3 second Ortholux Luminous testing using metallic brackets was over 20 Mpa at 24hrs (James, 2009).

The Valo Ortho by Ultradent became available in 2008 and is an example of a third generation LED curing light. The Valo Ortho can produce power densities up to 3200 mW/cm^2 in plasma emulation mode which is 4 times greater than its predecessor the Ultra-Lume 5 from Ultradent with a power density of approximately 800 mW/cm^2. The Valo Ortho uses three different LED chips to produce a light 'footprint' with central wavelengths at 405 nm, 445 nm and 465 nm. This is referred to as "polywave" spectrum capabilities and allows the light to cure resins with photo-initiators with peak absorption wavelengths that may differ from that of camphorquinone. The Valo Ortho has standard, high power and plasma emulation modes with curing interval settings at the plasma emulation mode of 3, 6 and 12 seconds. The light tip of the Valo Ortho is 10mm in diameter and the entire light is milled from one piece of billet aluminum using CAD/CAM technology making it extremely durable (Pelissier, 2011).

Figure 2: Ortholux Luminous (3M Unitek)

Figure 3: Valo Ortho (Ultradent)

Related Studies

As LED technology continues to improve, it has become apparent that there has been a trend for manufactures to increase the power densities of these lights while recommending shorter curing times. As a result, in vitro and in vivo investigations are needed to analyze the new generations of LED curing lights by examining the bond strengths of orthodontic brackets while focusing on the theory of reciprocity between power density and curing time. It is important to keep in mind that there may be a maximum limit of clinically useful power density. The following publications are similar to the current study in that they reported data on shear bond strengths with an emphasis on their relationship to energy density.

In 2011, Pinto et al. did a shear bond strength evaluation of metal orthodontic brackets cured with three different types of LED curing lights with different power densities. The study was conducted on 60 bovine incisors that were split into 4 test groups of 15 teeth each. The three lights tested were the Ultra LED XP (Dabi Atlante, Ribeirao Preto, SP, Brazil), the Ortholux LED (3M Unitek), and the Radii LED (SDI, Victoria, Australia). Respective power densities of the LED lights according to the manufacturer were 300-500 mW/cm^2, 1000 mw/cm^2 and 1400 mW/cm^2. However, it was mentioned that the output values were checked with a Demetron radiometer prior to testing and that their actual respective outputs were only 150, 850 and 800 mW/cm^2. This indicated that each light was producing less power than the manufacturer had specified. Each bracket was cured for 40 seconds—10 seconds from each side of the bracket. The results of this particular study showed that the two LED lights with the greater power density (output of > 800 mW/cm^2) produced bond strengths that were higher on average than the LED with the decreased power density (150 mW/cm^2) and the control QTH lamp (Pinto et al., 2011).

Cerekja et al. 2011, examined 240 extracted human premolars bonded with new high intensity LED curing lights (Blue Phase G2, 1200 mW/cm^2) and the new high power halogen lamps (Swiss Master, 3000 mW/cm^2) at shorter polymerization times. In addition, half of each test group was exposed to thermocycling from 5 degrees Celsius to 55 degrees Celsius for 24 hrs before testing. The halogen lamp was tested at 2, 3 and 6 seconds and the LED light was tested at 10 and 20 seconds. The results showed that the high powered halogen lamp reduced curing time without compromising bond strength suggesting that even halogen lamps can be used at very short curing intervals if the power density is increased substantially. The curing time could be reduced to 6 seconds with the halogen lamp (3000 mW/cm^2) and 10 seconds with the LED curing light (1200 mW/cm^2) without compromising shear bond strength of the bracket. Also, thermocycling did not seem to have an effect on the brackets unless there was inadequate polymerization as seen with the 2 and 3 second halogen groups (Cerekja et al 2011). The results of this study suggest that when power density is increased to 3000 mW/cm^2 with QTH lamps, they can produce acceptable bond strengths at very short curing times. However, it was mentioned in the discussion that an energy density of 6000 mJ/cm^2 produced by curing at 3000 mW/cm^2 at 2 seconds was not sufficient (Cerekja et al 2011). This supported previous claims that there may be an upper limit to the maximum power density required for bonding based on the maximum polymerization rate of the composite resin (Mavropolous et al., 2008).

The results found by Cerekja et al. in 2011 are in conjunction with two studies done in 2005 by Staudt et al., analyzing the shear bond strengths of orthodontic brackets cured with QTH lamps at increased power densities. In one study, bond strengths were analyzed with a set curing time of 4 seconds and increasing power densities from 500-3000 mW/cm^2 at 500 mw/cm^2 increments. The results suggested that there was a direct effect of power density on shear bond strength and that an exponential relationship exists between the two. Also, shear bond strengths comparable to the control group could only be obtained at a the shortest curing interval of 4 seconds if the highest power density of 3000 mW/cm^2 was used (Staudt and Krejci et al, 2005).

Another study done by Staudt et al. in 2005 analyzed a high power QTH lamp (3000 mW/cm^2) at 2, 3 and 6 seconds when compared to a control (1600 mW/cm^2 for 40 seconds) and a plasma arc lamp (1600 mW/cm^2). Their results suggested that the high power QTH lamp could produce shear bond strengths at 3 and 6 seconds that were comparable to the control QTH light and the plasma arc light at 40 seconds and 4 seconds respectively. The results also suggested that although the increased power density resulted in higher bond strengths at decreased curing times, the results seemed to follow an *exponential model* where further increases in power densities may cease to reduce curing time considerably (Staudt et al., 2005).

In addition to the publications done by Staudt et al., there have been numerous similar studies done in Geneva, Switzerland that have used bovine incisors to analyze the relationship between exposure time, power density and shear bond strength. In 2005, Mavropoulos et al, analyzed new (second generation) of intensive LED curing lights. Bovine incisors were used to examine shear bond strengths of metallic brackets bonded with two different LED curing lights with power densities of 800 mW/cm^2 and 1000 mw/cm^2-. The brackets were cured at 5 and 10 second intervals and were then compared with a QTH lamp (900 mW/cm^2) cured at 40 seconds. The results showed that the new intensive LED lights could produce bond strengths in 10 seconds that were comparable to the QTH lamp at 40 seconds. However, when cured for 5 seconds, the bond strengths were significantly lower (Mavropoulos, 2005).

In 2008, Mavropoulos et al. did another study focusing on "total energy" and the concept of reciprocity between curing time and power density. This study used QTH lamps and bovine incisors to analyze the shear bond strengths obtained at different total energy densities obtained with various combinations of power densities and curing times. For example, a total energy of 12,000 mJ/cm^2 could be analyzed after curing at 3000 mW/cm^2 for 4 seconds, 2000 mW/cm^2 for 6 seconds, 1000 mW/cm^2 for 12 seconds and so on. Multiple combinations and overall energy densities were compared and contrasted. The study concluded that even a weak power density could produce sufficient bond strengths if used for up to 40 seconds and that 4 seconds seemed to be the lower limit of time required for orthodontic bracket bonding. This study agreed with the findings of the investigations done by the same group suggesting that the relationship between power density and curing time follows an exponential model. It was suggested that the upper limit of useful power density was approximately 3000 mW/cm^2. It should be mentioned, however, that the study did not examine any power densities above 3000 mW/cm^2 (Mavropoulos et al., 2008). It was also suggested that power density seemed to have an advantage over curing time in terms of curing metallic brackets. In summary, the authors stated that "the concept of reciprocity between power density and exposure time did not hold true for the bonding of metallic orthodontic brackets" (Mavropoulos et al. 2008).

In 2005, Silta et al. analyzed the effects of shorter polymerization times with the "latest generation of light-emitting diodes". Extracted human molars were used to compare 3 different curing lights at 6, 10 and 20 seconds. Two LED curing lights with power densities of approximately 1000 mW/cm^2, were compared to a high power QTH lamp. However, the exact power densities were not mentioned except for that a Demetron 100 radiometer was used to be sure that the light output was greater than 400 mW/cm^2. The results showed that there was a significant difference in shear bond strengths between curing times with the 20 second cure being the most effective. It also showed that one of the LED curing lights (Ortholux LED) was significantly inferior to the other LED light and the QTH light (Ultralume LED 5 and the Optilux 501). In summary, the findings suggested that not all LED lights are created equal, and for the most reliable bond strength, a 20 second cure should be used when bonding with an LED light with a power density of approximately 1000 mW/cm^2 (Silta et al., 2005). One interesting aspect of this study was that the brackets were tested at 30 minutes after bonding instead of 24 hours and the mean bond strengths were all much lower when compared to other studies.

Swanson et al. in 2004 did a study examining LED lights at various polymerization times. This study examined three different LED curing lights (GC e-light , Elipar FreeLight, Ultralume LED 2). These lights were compared to the control QTH lamp (Ortholux xt). The metal brackets were bonded to extracted human molars and bonded at curing times of 10, 20 and 40 seconds. Similar to the study done by Silta, the power densities were verified to be greater than 400 mW/cm^2 but were not discussed; based on the time of the publication, it can be assumed that all three of the LED lights had power densities that were at or below 1000 mW/cm^2 . The results showed that there were significant differences between the different LED curing lights. In addition, the results suggested that there were differences between the same light at different curing times. However, all groups recorded shear bond strengths that were above the 8 MPa threshold as reported by Reynolds (Swanson et al., 2004).

A 2010 study done by Dall'Igna et al. used bovine incisors to compare an LED curing light with a power density of 800 mW/cm^2 (Ortholux LED 3M-Unitek,) to a plasma arc light with a power density of 1800 mW/cm^2 (Apollo 95E; DentMed Technologies,). The LED light was examined at 5, 10 and 15 seconds and the plasma arc light at 3, 6 and 9 seconds. The results suggested that the LED curing light could produce bond strengths at 5 and 10 seconds that were clinically acceptable and similar to the plasma arc light at 9 seconds. Also, the mean SBS values of the LED group were higher than those of the plasma arc group. The study suggested that LED and plasma arc curing units resulted in decreased time needed in order to cure composite adhesives (Dall'Igna 2010).

A similar study done by Yu et al. in 2007 used extracted human premolars to compare plasma arc lights with a power density of 1898 mW/cm^2 to a new intensive LED curing light (2nd generation) with a power density of 1000 mW/cm^2. The brackets were cured at 4, 6 and 8 second intervals. Their results showed that using the LED curing lights at the 8 seconds and the plasma arc light for 4 second light burst produced shear bond strengths that were clinically acceptable and equal to the QTH lamps at 40 seconds (Yu et al, 2007).

Gronberg et al, 2006 examined the second generation of LED curing lights at different curing intervals of 5, 10, 20 and 40 seconds. Their results suggested that all curing times longer than 10 seconds were clinically acceptable. In addition, the ARI scores of the 5 second group produced a higher number of 3 scores which was attributed to their being less polymerization occurring within the mesh bracket pad as a result of indirect polymerization passing through the underside of the bracket. This study also examined the effect that the amount of distance between curing light and adhesive had on shear bond strength and found that there was no difference in bond strengths between brackets cured at 1mm and 10mm from the bracket (Gronberg et al., 2006).

In summary, recent data has suggests that there seems to be an exponential relationship between SBS, power density and curing time (Staudt et al, 2005). It has also been suggested that there may be no benefit of increased power density above 3000 mW/cm^2 and curing times less than 4 seconds when using QTH lamps(Mavropolous et al., 2008). Although power plasma arc lights and QTH lamps with power densities of 3000 mW/cm^2 have been done, there has been no published data using LED curing lights with power densities greater than 1800 mW/cm^2. This information is relevant and necessary now that there are LED curing lights with power densities of 4-6000 mW/cm^2 and recommended curing times of 3 seconds. The current research hopes to clarify some of these questions.

MATERIALS AND METHODS

The current study design will mimic similar studies done in the past with the previous generations of curing lights. Ninety deciduous lower bovine incisors will be collected and stored in .2% thymol solution (anti-bacterial/anti-fungal) for a period not to exceed three months. Teeth with surface irregularities, noticeable wear or excess convexity will be excluded.

Mounting Procedure

The ninety bovine incisors will be mounted following the collection and decontamination process. Particular attention will be used in order to ensure that the enamel surface to which the bracket is bonded is parallel to the shearing force of the MiniBionix II.

First, the roots of the teeth will be scoured with a heatless stone for retention. Then, using rope wax and a dental surveyor, the teeth will be custom-mounted using a level mounting platform to position the facial surface of the incisor flat and parallel to the surface of the mounting arm. Once positioned, a plastic cylinder is placed around the mounted tooth and JET acrylic is poured in and around the root of the tooth up to the cemento-enamel junction. After the JET acylic has secured the tooth, the encapsulating cylinder is removed and the mounting procedure is complete ensuring that the vector of the shearing force during testing will be exactly parallel to the bonding surface of the bracket for each tooth.

Figures 4-8 depict some of the initial steps involved with mounting the teeth and ensuring parallelism between the enamel bonding surface and the shearing force represented by the vertical arm of the dental surveyor.

Figure 4: Perpendicular Lateral view

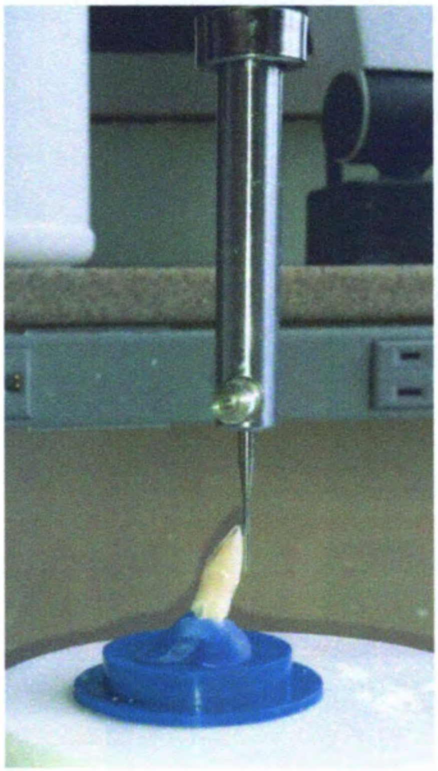


Figure 5: Centered Labial View

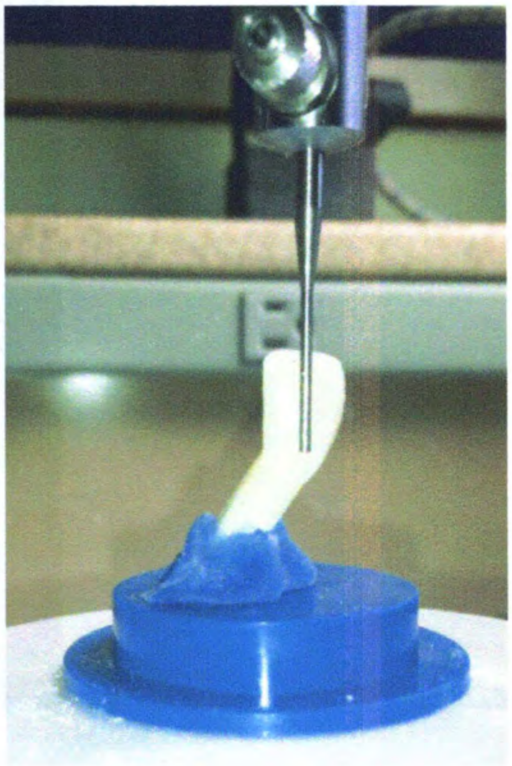


Figure 6: Plastic Mounting Cylinder

Figure 7: Mounted Bovine Incisor

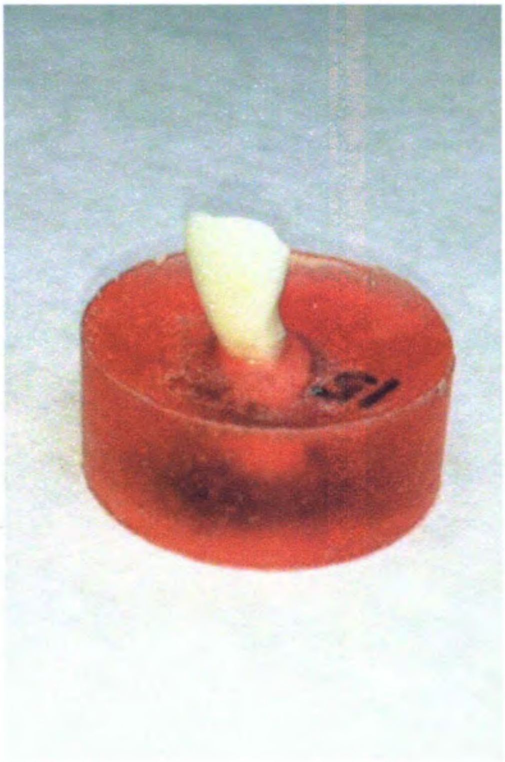
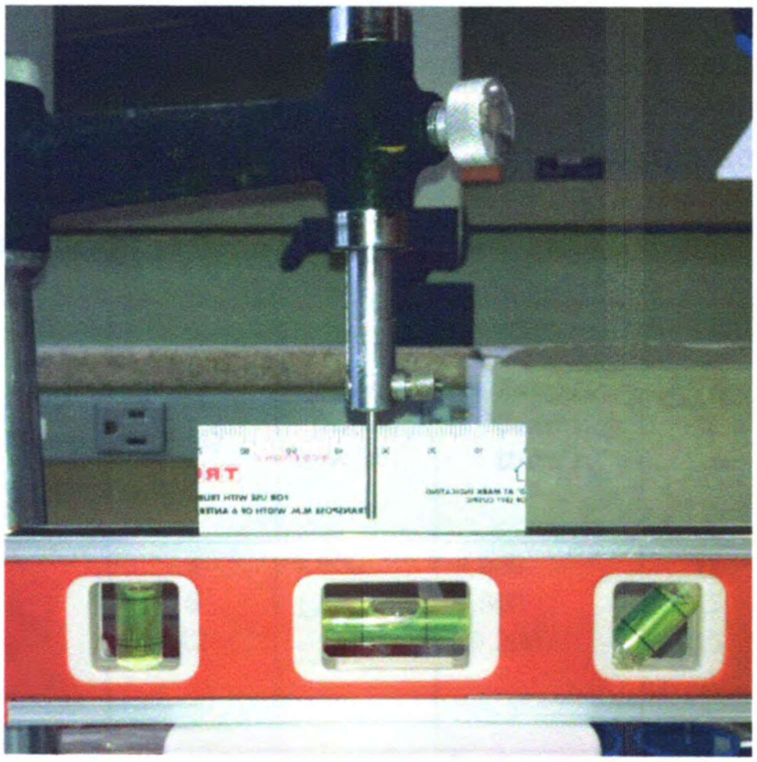


Figure 8: Confirming Parallelism



Bonding Procedure Part I

Once the teeth are carefully mounted, they will randomly be assigned to six different test groups. Each test group will be comprised of 15 teeth which will be prepared and bonded according to the specifications described in the following tables:

Table 1: Test Group Design

Curing Light	Test Group	Exposure (sec)	Power Density (mW/cm^2)	Energy Density (J/cm^2)	N	Tip Diameter	Wavelength (nm)	Light Position
Ortholux^{TM} Luminous (3M Unitek)	A B C	3 6 12	1,600 1,600 1,600	4,800 9,600 19,200	15 15 15	8 mm	430-480	Time split ½ mesial/ ½ distal, 3s cure from the gingival
Valo Ortho (Opal Orthodontics)	D E F	3 6 12	3200 3200 3200	9,600 19,200 38,400	15 15 15	10 mm	405-465	Time split ½ mesial/ ½ distal, 3s cure from the gingival

Bonding Procedure II

The brackets will be bonded according to the following specifications and are similar to those used in previous studies (Mavropolous et al. 2008):

Table 2 :Bonding procedure

Procedure	**Time**	**Material**
1. Cleaning	**15 sec**	Fluoride Free Pumice applied with slow speed prophy cup
2. Rinsing	**20 sec**	Tap Water
3. Drying	**5 sec**	Oil-Free Air
4. Etching	**30 sec**	35% Phoshoric Acid Etch - Transbond XT etching gel
5. Primer	**n/a**	Transbond XT Light Cure Adhesive Primer (1 thin coat)
6. Bracket placement	**n/a**	Adhesive Pre-Coated (APC) .022 Victory Series bracket (3M Unitek) - right maxillary cental incisor- placed using the shearing plate at the center of the tooth to be sure that the bracket edge is perpendicular/parallel to the shearing force. Excess adhesive removed with explorer
7. Light Cure	**n/a**	*Test group dependent*; done to manufacturer's recommendations. **See table 1**
8. Storage	**24 hrs**	Mounted/bonded teeth are stored in 37 degree tap water for 24 hrs before SBS testing
9. SBS	**n/a**	Samples will be placed in the lower jaw of the MTS 858 Mini Bionix II and stressed with a chisel rod in an occluso-gingival direction at a crosshead speed of .5mm/minute. Force values are recorded at the point of bond failure and measured in Newtons.

SBS Test Details

It is important to note that in this study a Demetron radiometer (Demetron Inc.) was used to verify the power density of each light prior to bonding the brackets. The radiometer reading was just under 1600 mW/cm^2 for the Ortholux Luminous, and at the 2000 mW/cm^2 limit for the Ortho Valo. Unfortunately, there are no commercially available LED radiometers that can read LED radiation values higher than 2000 mW/cm^2.

The MTS Mini-Bionix II was used to analyze the shear bond strengths of the brackets in Newtons. This study will use a chisel-shaped rod to shear the brackets. The edge of the chisel was sharpened to fit into the undercut between the bracket wing and the bracket pad. The shearing force will be applied at .5 mm/min over a distance of 2mm until bracket failure. The MTS Mini-bionix II and an example test specimen are pictured in Figures 9,10.

Figure 9: MTS Mini-Bionix II

Figure 10: Mounted Tooth at Test Time

ARI Score:

Following the debonding procedure, an adhesive remanent index (ARI) score will be recorded using a 10.7X microscope (Seiler iQ Surgical Scope) to determine the mode of bond failure. The ARI score will be assessed on a 4 point scale as established by Atrun and Bergland and are as follows (Artun and Bergland et al., 1984):

0 – No Adhesive left on tooth surface
1 – Less than half of the adhesive left on the tooth surface
2 – More than half of the adhesive left on the tooth surface
3 – All adhesive left on the tooth with a distinct impression of the bracket base

Data Calculation:

The shear bond strength will be recorded digitally in Newtons at the point of bracket failure. For shear bond strength studies, MegaPascals (Mpa) are used to describe the amount of debonding force required per unit of surface area. This value is derived based on the surface area the adhesive pre-coated maxillary right central incisor bracket from 3M Unitek (Monrovia, California) which was 12.16mm^2 . The equation to convert Newtons to MegaPascals is as follows:

$$\textit{Mega Pascals (Mpa)} = \textit{force (Newtons)} / 12.16\ mm^2\ \textit{(bracket surface area)}$$

Statistical Analysis:

The standard deviation from previous investigations was used to calculate sample size and power estimations. A sample size of at least 12 in each of the 6 test groups (2 lights, 3 time points) was expected to provide 67.5% power (*alpha* = 0.05) to detect a difference of 5 MPA between the light types at 12 seconds. While >85% power (*alpha* = 0.05) was expected for detecting a difference of 5 MPA between 3 sec and 12 sec for both light types.

Following data collection, the values were converted into MegaPascals and then analyzed using the Shapiro-Wilk tests for normality-assumptions. These results showed that the data generally followed a normal distribution, and energy densities between lights and curing times were compared using a series of one-way and two-way ANOVA analyses with Tukey's method for multiple comparisons (*alpha* = 0.05).

The ARI scores from each of the six test groups were tabulated according to score. The data were then compared using non-parametric Kruskal-Wallis tests (*alpha* = 0.05). The Kruskal-Wallis test will provide information about statistical differences that may exist in the method of debonding for each of the test groups.

All statistical analyses were performed using SAS ® Proprietary Software, Version 9.2, SAS Institute Inc., Cary, NC, U.S.A.

RESULTS

Overall, there were 86 specimens used in this study. Of the four teeth that were excluded from the study, two of the specimens had their data files over-written during testing while using the Mini Bionix II software and two had bonding issues related to the mounting procedure. After the bond failures were recorded in Mpa, the results were tabulated. The number of test specimens per test group, mean, median and standard deviation are listed in Table 3. Additionally, the *p-values* for the Shapiro-Wilk tests for normality and the 95% confidence intervals for each mean are shown.

The mean shear bond strength for each light increased with increased curing time. However, when using a one-way ANOVA analysis to examine each light independently by comparing between curing times of 12, 6 and 3 seconds, there were no significant differences in mean shear bond strengths according to curing time for either light type (Valo Ortho: $p = 0.9064$, Ortholux Luminous: $p = 0.1958$). A second one-way ANOVA analysis was performed to examine differences between the two light types (Valo Ortho versus Ortholux Luminous) at each curing time interval; these results showed no significant differences according to light type for any of the curing times (3 seconds: $p = 0.3787$, 6 seconds: $p = 0.4708$, 12 seconds: $p = 0.8173$). Figure 12 shows the mean shear bond strength for each of the test groups with the upper and lower values at 95% confidence limits.

In order to analyze total energy density, each test group was compared individually to the others. The two-Way ANOVA analysis to assess for effect modification of light according to time showed no significant interaction ($p = 0.6875$). Further, when

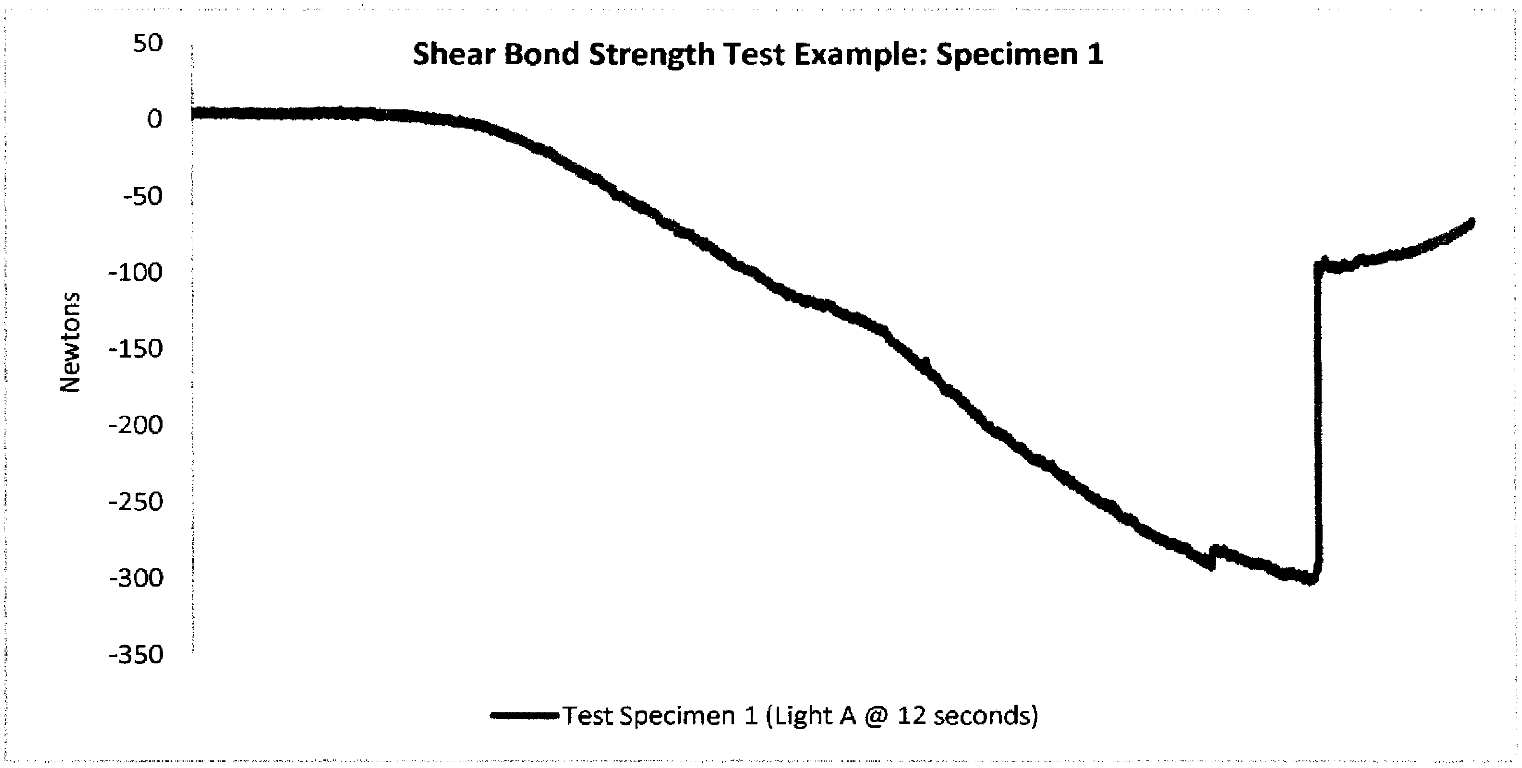
Table 3: Numerical Results for Shear Bond Strength Testing

Curing Light	N	Mean SBS (Mpa)	Standard Dev	Median	Shapiro-Wilk (p value)	95% Confidence Interval	
						lower bound	upper bound
Ortholux Luminous (1600 mW/cm2)							
3 Sec	15	24.99	4.92	24.07	0.779	22.13	27.86
6 Sec	16	25.72	4.98	26.99	0.754	22.94	28.49
12 Sec	13	28.37	5.28	28.27	0.445	25.29	31.45
Valo Ortho (3200 mW/cm2)							
3 Sec	12	26.95	6.42	26.57	0.259	23.74	30.15
6 Sec	14	26.97	4.31	27.11	0.961	24.00	29.93
12 Sec	16	27.82	7.06	27.29	0.977	25.04	30.59

comparing all 6 groups individually, there were no significant differences (Tukey-Kramer *alpha* = 0.05).

The MTS Mini Bionix II and associated software package were used to test the shear bond strength (SBS) limits for each specimen. The data plot for each specimen was recorded as a negative value in Newtons (N) which was then converted to MegaPascals (Mpa) by dividing the bond failure amount by the surface area of the bracket base, 12.16 mm^2. The results were then recorded as positive values. Figure 11 is an example of one specimen depicting the typical results for each of the 90 SBS tests. In this example, Specimen 1 was bonded using light A (Valo Ortho) for 12 seconds and the bracket debonded at a force of - 303.14 Newtons.

Figure 11: Example Shear Bond Strength Specimen



** Note – the horizontal x axis represents the distance in mm that the edge of the chisel attachment (shearing force) traveled in mm (setting = .5mm/min)*

Once the brackets were debonded, the teeth were analyzed using the adhesive remnant index (ARI) score described in the materials and methods. Table 4 illustrates the tabulated scores for each of the test groups. In terms of the ARI score for each of the 86 samples, there were no scores of 0 or 1 and the median score for each of the test groups was a 3. The Kruskal-Wallis (non-parametric) test was used to compare the ARI scores between each of the test groups, with results showing no significant differences (*p*=0.32).

Table 4: Adhesive Remnant Index Scores

	0	1	2	3	Median
Ortholux Luminous					
3 Sec	0	0	5	10	3
6 Sec	0	0	3	13	3
12 Sec	0	0	2	11	3
Valo Ortho					
3 Sec	0	0	4	8	3
6 Sec	0	0	1	13	3
12 Sec	0	0	1	15	3

DISCUSSION

The results of the current study suggest that when using new high intensity LED curing lights with power densities of either 1600 or 3200 mW/cm^2, that a curing time as short as 3 seconds can produce shear bond strengths in vitro that are clinically acceptable when compared to the 6-8 MPa suggested by Reynolds et al. in 1975. In addition, although the mean SBS values of the new LED lights at 3 second exposure times were slightly less than the bond strengths produced at 6 and 12 seconds; these differences were not significant. This suggests that a 3 second cure per bracket may be advantageous clinically due to increased efficiency and decreased susceptibility to contamination when compared to longer curing intervals.

The results of the current study also suggest that there is not a significant difference in the bond strengths produced by the two different curing lights. This would imply that there is no distinct advantage of using an LED curing light with an increased power density of 3200 mW/cm^2, even though it is exactly twice the power density of curing light with a 1600 mW/cm^2 output. These findings seem to support claims made in the past that there may not be much clinical benefit in power densities greater than 1000 mW/cm^2 due to the maximum conversion rate of composite resins during polymerization (Musanje et al., 2003; Mills et al., 1999). However, the different design of the two lights may play a role in curing efficiency. Certain variables such as tip diameter, LED chip technology and the emission spectrum wavelength could produce differences in bond strength between the two lights. It has been suggested that lights with multiple wavelength emission spectra, such as the Ortho Valo, may cause interferences in the activation of the photo-initiator camphorquinone (Pelissier, 2011).

These findings are very interesting when compared to a study done in 2008 by Mavropolous et al., with a very similar experimental design. One major difference, however, was that Mavropolous et al. used high power QTH lamps with power densities ranging from 30 mW/cm^2 to as high as 3000 mW/cm^2. The study done by Mavropoous et al., recorded its highest MPa of 22.49 MPa when using the QTH lamp at a power of 3000 mW/cm^2 for 8 seconds, the current study recorded the highest bond strength of 28.37 Mpa when using a high intensity LED light at 1600 mW/cm^2 for 12 seconds. Our standard deviation was also similar to this previous study, with Mavropolous et al recording a range from 4.67-7.12 MPa, and the current study ranging from 4.92-7.06MPa.

One of the conclusions made by Mavropolous et al. was that there may be no benefit of power densities greater than 3000 mW/cm^2 and that a curing time of less than 4 seconds could not produce bond strengths that were clinically acceptable (Mavropolous et al., 2008). Although, those findings may be true in terms of the QTH lamps tested by Mavropolous et al., the current findings seem to support the first claim but are contradictory to the latter when using the newest high intensity LED curing lights. This in vitro investigation produced bond strengths that were acceptable with only 3 second exposure times. However, the bond strengths produced at 1600 mW/cm^2 appeared similar to those produced at 3200 mW/cm^2. This finding seems to support the assumption that SBS values seem to follow an exponential model. Further, increases in power density past a certain limit may not necessarily produce any clinically measurable benefit (Mavropolous et al., 2008; Staudt elet al. , 2005; Musanje et al., 2003).

In terms of absolute MPa, the results of this study were also comparable to a similar study done by 3M Unitek, the manufacturer of the Orhtolux Luminous curing light, performed just before its introduction in 2009(James et al., 2009). Although the intricate details of the study were not reported, the mean SBS values of metallic brackets debonded from bovine incisors at 24 hours by James et al. were approximately 22 MPa when using the same Ortholux Luminous at a curing time 3 seconds. The current study recorded similar bond strengths with a mean of 24.99 MPa when using the same light for 3 seconds and debonding at 24 hrs.

Although it is helpful to compare the mean shear bond strength values of this study to previous studies with a similar design, it is important to note that the recorded values for bond strengths are difficult to compare across studies due to several variables involved with the experimental design. Some examples of the variables that tend to limit comparison are the type of tooth used, the etch/prime/adhesive system employed, type of bracket (material, surface area and thickness), curing light type, curing time, curing distance, the duration and storage from bonding to debond, and the mechanics and attachments used for debonding (Pinto et al., 2011). Due to these discrepancies, although the results of a shear bond strength study provide valuable information based on the specific hypothesis tested, it may be difficult, if not impossible to accurately compare the absolute mean shear bond strengths from one study to another.

The mean shear bond strengths found between the test groups in this study ranged from 24.99 MPa (1600 mW/cm^2 @ 3 seconds) to 28.37 MPa (1600 mW.cm^2 @ 12 seconds). These SBS values are comparable to other studies done using similar overall energy densities and bonding techniques (Mavropolous et al. 2008, James et al. 2009). However, these mean shear bond strengths appear to be very high when compared to the minimum clinically acceptable bond strength of 6-8 MPa as suggested by Reynolds et al. in 1975 (Reynolds et al., 1975). Part of the reason for this discrepancy can be accounted for due to the shear bond strength differences that occur in vitro when compared to those in vivo. In 2003, a study done by Murray et al. compared the differences between bond strengths of brackets in vivo and in vitro. They compared brackets bonded and stored in virto in 37° Celsius water to brackets bonded in the same fashion but worn in vivo on a removable appliance at 4 weeks and found the bond strengths of the latter to have bond strengths approximately 28% less at 4 weeks. The reason for the decreased bond strength in vivo are suspected to be a result of biodegradation occurring from numerous factors including components in saliva, erosion from food particles, physical wear, bacterial activity and temperature fluctuations (Murray et al., 2003). As a result, the bond strengths found in vitro are expected to be higher on average compared to what will actually be found in vivo.

In addition, SBS values were found to increase in strength up to their peak at 24 hrs following bonding and then decrease over the next 24 months (Oesterle et al., 2008). This would suggest that these values were at their peak strength at the time of bond strength testing.

Future studies should be designed in order to continue to monitor the trend of increasing shear bond strengths as photo-polymerization technology, adhesives and bonding techniques improve. As reported by Retief et al., enamel fractures can occur with bond strengths as low as 13.5 Mpa (Retief et al., 1974). Although practitioners and manufactures strive for bonding techniques with the lowest bracket failure rate during treatment, it is even more important that permanent damage to the enamel is not done when the brackets are debonded following treatment.

When looking at the SBS values in terms of total energy density, it is interesting to note that the SBS values for each light did increase with increased total energy (J/cm^2). For the Ortholux Luminous (3M Unitek) the energy densities of 4800, 9600 and 19200 J/cm^2 were analyzed, while for the Valo Ortho (Ultradent) of 9600, 19200 and 384000 J/cm^2 . Although the SBS values between the two lights cannot be compared in terms of total energy density due to factors in light design, it is safe to say that each of the relationships between the SBS values and the energy densities appear to follow an exponential model. This finding is similar to that suggested by previous studies (Staudt et al., 2005; Mavropolous et al., 2008). In addition to power density and curing time, a predominant factor in the exponential relationship seen between SBS value and energy density is the maximum polymerization rate of the composite resin adhesive used in the metallic adhesive pre-coated brackets (3M Unitek) as employed in this study.

In terms of ARI scores, there were no scores of 0 or 1, and the predominant score given was a 3. In addition, there was no significant difference found in terms of ARI score recorded between test groups. This would suggest that regardless of the curing light used, or a curing time of 3, 6 or 12 seconds, the mode of failure for each bracket was similar. A median score of 3 would suggest that the weakest point of the bonding interface was the area between the adhesive and the bracket pad which is ideal when debonding.

One of the major limitations of this study was that it was an in vitro investigation using bovine enamel. There was also no thermo-cycling employed in this study although previous studies that did use thermo-cycling did not produce significantly different SBS values at 24 hrs (Signorelli et al., 2006). In the future, in vivo investigations using human enamel will be needed to test the shear bond strength of metallic brackets using the new high intensity LED curing lights. In addition to the high intensity LED curing lights examined in this study, there are new high intensity LED curing lights that have been introduced to the orthodontic market with power densities as high as 4000-6000 mW/cm^2 (FlashMax P3, Rocky Mountain Orthodontics). Similar studies comparing these lights may produce valuable information regarding a possible 'ceiling' for power density in terms of the clinical benefits in shear bond strength resulting from increased power density. A study using one LED curing light with multiple power setting would allow for different combinations of power density and curing time similar to that done by Mavropolous et al. in 2008 using QTH lamps. This design would be ideal in order to analyze specific relationships regarding total energy density for new high intensity LED curing lights.

SUMMARY AND CONCLUSIONS

The current in vitro investigation evaluated two new high intensity LED curing lights, the Valo Ortho (Ultradent) and the Orhtolux Luminous (3M Unitek). Prior to 2012, there has been minimal research published on the bond strength capabilities of LED curing lights with increased power densities ranging from 1600-3200 mW/cm^2.

The following conclusions can be drawn from the current in vitro investigation which used bovine incisors to test the shear bond strength of metallic brackets cured at exposure times of 3-,6-, and 12-seconds with either the Valo Ortho (Ultradent) @ 3200 mW/cm^2 or the Ortholux Luminous (3M Unitek) @ 1600 mW/cm^2:

1. When using either of the high intensity LED curing lights, an exposure time as short as 3 seconds produced bond strengths that were not significantly different from those that were produced at 6-, and 12-seconds. All of the bond strengths, regardless of curing time, appeared to be similar which suggests clinical acceptability.
2. There were no significant differences between bond strengths produced by the Valo Ortho (Ultradent) at a power density of 3200 mW/cm^2 compared to the Ortholux Luminous (3M Unitek) at a power density of 1600 mW/cm^2 when curing for 3-, 6- or 12-seconds.

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