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Polymerization Efficiency of Different Photocuring Units Through Ceramic Discs

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Clinical Relevance

The ability of modern light curing units to photocure luting resin through ceramic restorations is dependent on the type of light source, ceramic thickness and use of a self-curing catalyst.

SUMMARY

This study compared the ability of a variety of light sources and exposure modes to polymerize a dual-cured resin composite through ceramic discs of different thicknesses by depth of cure and Vickers microhardness (VHN). Ceramic specimens (360) (Empress 2 [Ivoclar Vivadent], color 300, diameter 4 mm, height 1 or 2 mm) were prepared and inserted into steel molds according to ISO 4049, after which a dual-cured composite resin luting material (Variolink II [Ivoclar Vivadent]) with and without self-curing catalyst was placed. The light curing units used were either a conventional halogen curing unit (Elipar TriLight [3M/ESPE] for 40 seconds), a high-power halogen curing unit (Astralis 10 [Ivoclar Vivadent] for 20 seconds), a plasma arc curing unit (Aurys [Degré K] for 10 seconds or 20 seconds) or different light emitting diode (LED) curing units (Elipar FreeLight I [3M/ESPE] for 40 seconds, Elipar FreeLight II [3M/ESPE] for 20 seconds, LuxOmax [Akeda] for 40 seconds, e-Light [GC] for 12 seconds or 40 seconds). Depth of cure under the ceramic discs was assessed according to ISO 4049, and VHN at 0.5 and 1.0 mm distance from the ceramic disc bottom was determined (ISO 6507-1). Medians and the 25th and 75th percentiles were determined for each group (n=10), and statistical analysis was performed using the Mann-Whitney-U-test ($p \leq 0.05$).

The results showed that increasing ceramic disc thickness had a negative effect on the curing depth and hardness of all light curing units, with hardness decreasing dramatically under the 2-mm thick discs using LuxOmax, e-Light (12 sec-

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onds) or Aurys (10 seconds or 20 seconds). The use of a self-curing catalyst is recommended over the light-curable portion only, because it produced an equivalent or greater hardness and depth of cure with all light polymerization modes.

INTRODUCTION

Significant development in adhesive dentistry during the past two decades has made ceramic both a widespread and scientifically accepted material for anterior and posterior restorations (Schmalz & Geursten, 2001). In most clinical cases, a dual-curing resin composite is used when bonding ceramic to enamel and dentin.

Polymerization of those dual-curing resins may be initiated chemically (self-curing catalyst) using benzoyl peroxide with a tertiary aromatic amine that acts as an electron donor to split the benzoyl peroxide into free radicals. Or, the polymerization process may be started by visible light commonly using the diketone camphorquinone as a photoinitiator (ADEPT Institute, 1996). The most efficient wavelength for inducing camphorquinone stimulation and formation of free radicals is between 450-490 nm, with a peak of maximum absorbtion at 468 nm. Therefore, curing devices should operate in the 400-500 nm wavelength range in order to provide adequate polymerization.

Until recently, halogen curing units were used to polymerize resin luting materials. These light sources usually provide power densities between 400 and 800 mW/cm^2 and cure composite resins within 40 seconds (Munksgaard, Peutzfeldt & Asmussen, 2000). However, this type of unit has several drawbacks. Rueggeberg and others (1996) pointed out that halogen bulbs have a limited effective lifetime of approximately 40 to 100 hours. The high operating temperatures of this type of source results in degradation of the bulb, the reflector and the filter over time, causing a reduction in their effectiveness (Barghi, Berry & Hatton, 1994). Furthermore, high intensity curing units may result in irreversible damage of the pulp tissue through temperature rise due to the photothermal effect (Uhl, Mills & Jandt, 2003a,b,c; Bouillaguet & others, 2005). To overcome these problems, new types of light-curing units, such as light emitting diodes (LEDs), have been developed. Instead of the hot filaments used in halogen bulbs, LEDs use junctions of doped semiconductors to generate light (Nakamura, Mukai & Seno, 1994). Hofmann, Hugo and Klaiber (2002) showed that the temperature rise in resin composite during polymerization was lower with LEDs compared to halogen units, reducing the potential risk of irreversible pulp damage. LEDs operate at a low wattage and are, therefore, mainly powered by rechargeable batteries, enabling them to be cordless. Their relatively narrow wavelength range (430-480 nm) is optimally suited for the activation of camphorquinone. However, a major drawback is that other photoinitiators, for example, Lucirin, Irgacure 640 and Phenyl-propane-dione (PPD), used in some resin composite and dentin bonding materials, absorb at a shorter wavelength than 450 nm and are, thus, not activated (Hofmann & others, 2000, 2002).

In an attempt to reduce exposure duration, high-power halogen curing units with power densities of up to 1200 mW/cm^2 and high–power LEDs up to 1000 mW/cm^2 have been developed. Another recently developed high intensity curing device is the plasma arc (PAC) light, generating power densities near 1800 mW/cm^2. These sources generate a very wide spectral emission and rely on extensive filtering to reduce output to that of visible light. Most current PAC lights emit radiation between 380 and 500 nm, thus providing energy to meet the needs of all types of photoinitiators.

Controversy exists in the relationship between exposure duration and degree of monomer conversion (Uno & Asmussen 1991; Hadechney & others, 1999; Peutzfeldt, Sahafi & Asmussen, 2000). However, conversion is generally considered a crucial factor for optimal physical properties and successful clinical performance of resin composite materials (Bayne, Heymann & Swift, 1994). Conventional halogen curing units with power densities of at least 400 mW/cm^2 and exposure durations of 40 seconds have been shown to provide adequate curing of resin composites (Rueggeberg, Caughman & Curtis, 1994) and may, therefore, be considered as "golden standards." Inadequate polymerization results in low conversion, with higher amounts of residual carbon double bonds causing inferior physical properties and increased water absorbtion and solubility. Furthermore, the increased release of residual, unreacted monomers jeopardizes the health of the dental pulp, especially in deep preparations (Hebling, Giro & Costa, 1999; Thonemann & others, 2002).

Inadequate curing of resin composite luting materials may be a problem, especially under ceramic restorations where these resins are used without a self-curing catalyst as is often practiced by dentists during the insertion of ceramic veneers. The reasons for this practice are that dentists believe that this technique will not affect cement cure. Also, they believe that there may be a slight yellowing of the resin luting material caused by the presence of self-cure amine-catalyst.

Therefore, this study examined the ability of different polymerization modes (halogen [conventional and high-power], LED [conventional and high-power], and plasma arc light curing) through ceramic restorations

by determination of the depth of cure and microhardness (VHN) using a resin composite luting material with and without the self-curing catalyst.

METHODS AND MATERIALS

A total of 360 ceramic specimens (IPS-Empress 2, color 300, Lot #C41418, Ivoclar Vivadent, Schaan, Liechtenstein) (4.0 mm in diameter and a height of 2.0 or 1.0 mm) were pressed in the IPS-Empress furnance. All specimens were etched with 10% hydrofluoric acid (IPS-Empress ceramic etching gel, lot C41654, Ivoclar Vivadent) for 60 seconds, rinsed for 60 seconds and air-dried. A silane (Monobond S, lot C 454444, Syntac Adhesive System, Ivoclar Vivadent) was then applied on the etched surfaces for 60 seconds and air-dried. Prepared specimens were randomly distributed as shown in Table 1. Subsequently, the ceramic specimens were placed in a cylindrical split stainless steel mold (4.0 mm in diameter and 6.0 mm in height). The conditioned surface of the specimens was facing upward. The resin composite luting material (Variolink II Base: Yellow 210/A3, lot D 08992, Ivoclar Vivadent) was applied on the top of the specimens either with or without the self-curing catalyst (Variolink II Catalyst: high viscosity type, lot C15156, Ivoclar Vivadent). Then, the ends of the mold were covered with a piece of a polyethylene stripe and a metal plate according to ISO 4049 (ISO, 2000) to displace excess material. The mold was inverted, and the resin composite luting material under the ceramic discs was exposed to light from a curing unit according to the manufacturer's recommendations (Table 2 and Figure 1) with the tip in contact to the ceramic disc. The irradiance profile and power density of each curing unit was measured using a spectrally resolving fiberoptic radiometer with an 80 mm integrated sphere (S2000, Ocean Optics, Netherlands). Each specimen end was covered with a metal plate after exposure to avoid further light irradiation.

Table 1: *Distribution of the Ceramic Test Specimens (*n=10 for each polymerization mode 1-9 [Table 2])*

360 ceramic specimens	180 ceramic specimens (height 1 mm)	90 specimens* (resin composite luting material used with self-curing catalyst)
		90 specimens* (resin composite luting material used without self-curing catalyst)
	180 ceramic specimens (height 2 mm)	90 specimens* (resin composite luting material used with self-curing catalyst)
		90 specimens* (resin composite luting material used without self-curing catalyst)

Depth of Cure

Immediately after irradiation, depth of cure was determined following ISO 4049 (ISO, 2000). The specimens were removed from the mold, and the uncured material

Table 2: *Light Curing Units Used in the Different Exposure Modes*

	Curing Unit	Code	Unit Type	Curing Mode	Exposure Duration	Power Density Given by the Manufacturer (mW/cm²)	Power Density Measured (mW/cm²)	Manufacturer
1	Astralis 10	AS	High-power halogen	ECS (esthetic cementation system)	20 seconds	1200	2260	Vivadent, Schaan, Liechtenstein
2	Elipar TriLight	ET	Halogen	Standard	40 seconds	800	815	3M/ESPE, Seefeld, Germany
3	Elipar Free-Light I	EF I	LED	Standard	40 seconds	400	347	
4	Elipar Free-Light II	EF II	High-power LED	Standard	20 seconds	1000	935	
5	LuxOmax	LU	LED	Standard	40 seconds	300	150	Akeda, Lystrup, Denmark
6	e-Light	eL 12	LED	Fast cure	12 seconds	750	490	GC Europe, Leuven, Belgium
7	e-Light	eL 40	LED	Standard	40 seconds	350	285	
8	Aurys	AU 10	PAC	Standard	10 seconds	1600	1669	Degré K, Schlittingheim, France
9	Aurys	AU 20	PAC	Standard	20 seconds	1600	1669	

was scraped away using a plastic spatula. The height of the cylinders of the remaining cured material and ceramic disc was measured with a digital micrometer (293-101, Mitutoyo, Tokyo, Japan) to a precision of 0.01 mm. The depth of cure was calculated by subtracting the thickness of the ceramic specimen from the determined value. Subsequently, these specimens were stored in a box to protect them against further light exposure before the surface hardness measurements.

Surface Microhardness (VHN)

The specimens were glued in plastic molds, with the ceramic surface facing the bottom of each mold. They were then embedded in a cold-curing, low-viscosity epoxy resin (EPO THIN, Buehler, Lake Bluff, IL, USA) and stored at room temperature in an opaque box. Hardening of the epoxy-resin was completed after 36 hours, and the specimens were removed from the molds. The resin composite luting material was reduced to a 1.2-mm thickness using a water-cooled, low-speed diamond saw (Leica SP 1600, Leitz, Wetzlar, Germany). The specimens were then wet polished (Metaserv, Buehler) to a final composite thickness of 1.0 mm using 240, 600 and 1000 grit silicon carbide paper discs (Carbimet, Buehler). The dimensions of diamond indentations of three randomly placed test sites were recorded in a hardness tester (Zwick, Ulm, Germany) (ISO 6507-1 [ISO, 2005]), and the subsequent Vickers hardness was determined. Measurements were made using a force of 2 N, which was applied for 15 seconds. After measuring, the grinding and polishing procedure was repeated until the specimens had a remaining composite thickness of 0.5 mm. Surface microhardness was again determined as described above. One clinician determined both the depth of cure and the Vickers hardness. All specimen preparations and measurements were performed in a darkened environment.

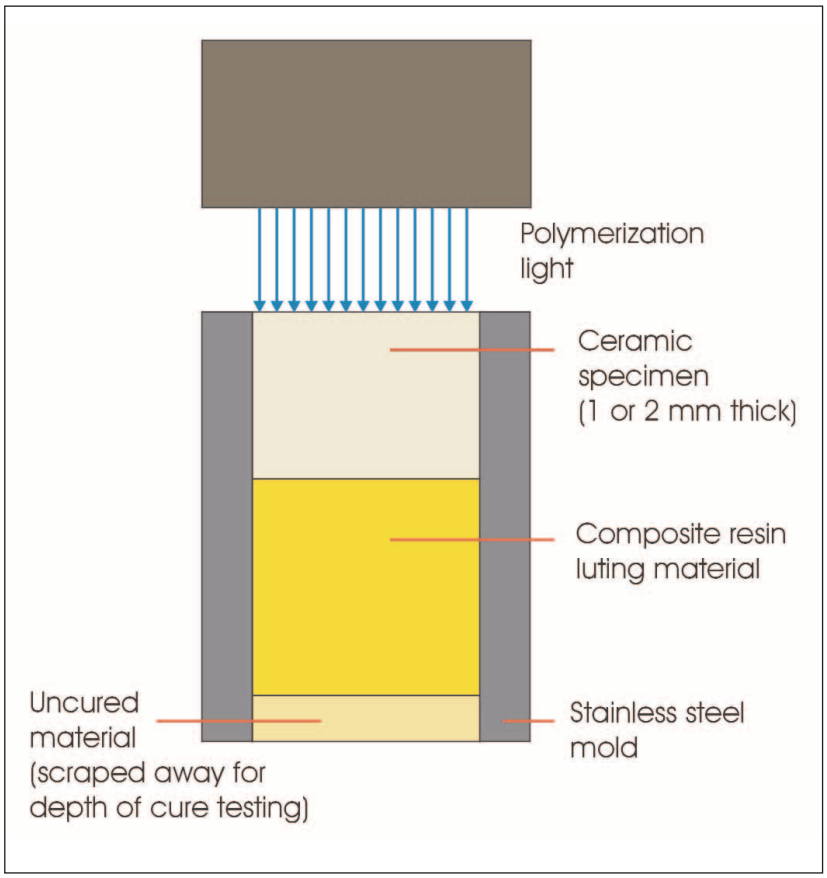

Figure 1: *Polymerization of resin composite luting material through the ceramic specimen.*

Statistical Analysis

Medians and the 25th and 75th percentiles of depth of cure and Vickers hardness were determined for each polymerization mode with and without catalyst. Statistical analysis was performed using the Mann-Whitney U test (SPSS/PC+, Vers 5.01, SPSS, Chicago, IL, USA) for pairwise comparisons among groups at the 0.05 level of significance ($p \leq 0.05$).

RESULTS

The measured light intensities of the curing units are shown in Table 2 and differed considerably in some cases from those stated by the manufacturers; for example, for the high-power halogen lamp, the output measured was almost double the information provided by the manufacturer.

Depth of Cure

The results of the depth of cure are shown in Figures 2 and 3 and in Table 3. The median depths of cure under the 1.0 mm ceramic specimens were always more than 2.4 mm for both with and without self-curing catalyst for all polymerization modes. Using no catalyst, eL12, AU 10 and LU showed significantly lower values compared to all other polymerization modes, with eL 12 and AU 10 still having lower values when used with catalyst.

The median depths of cure under the 2.0 mm ceramic specimens were always more than 1.1 mm for both with and without self-curing catalyst for all polymerization modes. Using no self-curing catalyst, LU showed significantly lower values compared to all other polymerization modes, but eL 12, AU 10 and AU 20 also showed median values below 2.0 mm. With the exception of AU 10, use of the self-curing catalyst always resulted in a greater depth of cure. Increasing ceramic thickness from 1.0 to 2.0 mm and using no self-curing catalyst resulted in significantly lower depths of cure, regardless of the light curing unit.

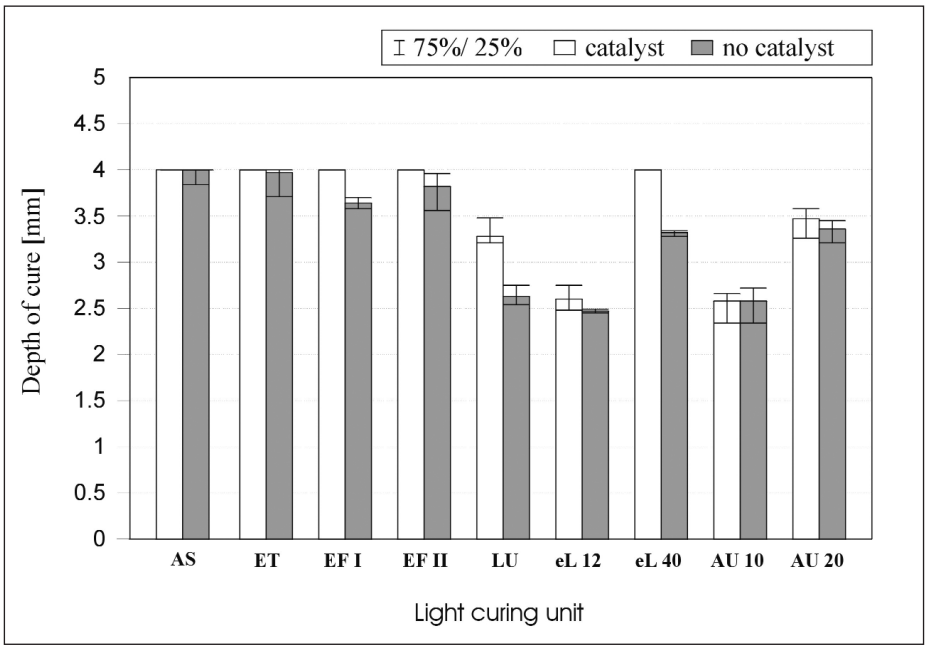

Figure 2: *Medians and 25/75 percentiles of the depth of cure of the resin composite luting material under the 1 mm ceramic restoration when used with and without self-curing catalyst with different polymerization modes.*

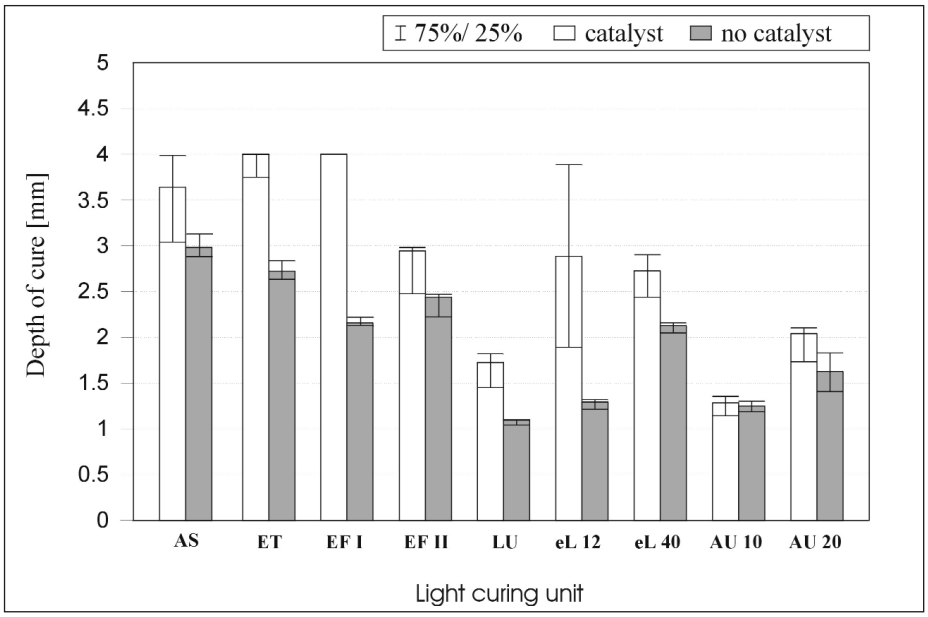

Figure 3: *Medians and 25/75 percentiles of the depth of cure of the resin composite luting material under the 2 mm ceramic restoration when used with and without self-curing catalyst with different polymerization modes.*

Vickers Hardness (VHN)

Microhardness values are shown in Figures 4 and 5 and Tables 4 and 5. The median hardness under the 1.0 mm ceramic specimens was between 58 and 30, and for the 2.0 mm ceramic specimens, it was between 56 and 3. For each ceramic thickness, use of a self-curing catalyst always produced higher hardness values for all polymerization modes, both in the 1.0- and 0.5-mm thick composite layers. Using no self-curing catalyst, hardness values in the 0.5-mm composite layer were always significantly higher compared to the 1.0-mm layer. Increasing ceramic thickness from 1.0 to 2.0 mm and using no self-curing catalyst always resulted in significantly lower hardness both in the 0.5- and 1.0-mm thick composite layers, with AS 20 as the only exception in the 0.5 mm layer.

DISCUSSION

Investigations into the performance of new curing technologies by measuring the physical and mechanical properties and the degree of conversion of composite materials are becoming increasingly available (Soh, Yap & Siow, 2003; Hofmann & others, 2002; Uhl & others, 2003). For measurement of conversion values, direct methods, such as infrared (Asmussen, 1982a) or laser raman spectroscopy (Louden & Roberts, 1983) are the most sensitive techniques, but they are very time-consuming and expensive (Shortall & Harrington, 1996). An indirect method, described as being very sophisticated, is the universal hardness test (Jung & others, 2001) where hardness is measured under load. However, this testing requires special equipment for use in a universal testing machine, which is why that data is very scarce to date. The measurement of hardness profiles using Vickers, Knoop or Rockwell methods are known to be reliable and are easy to perform indirect methods for investigating the degree of conversion of a composite material. Asmussen (1982b) showed a good correlation between hardness and degree of conversion by infrared spectroscopy.

Dual-curing resin cements should reach an adequate degree of conversion with and without light curing in areas that are not accessible to the curing light (el-Mowafy & Rubo, 2000). Variolink has been claimed to have a relatively weak chemical curing component (el-

Table 3: *Statistical Results of the Mann-Whitney-test: Pairwise Comparisons of Depth of Cure*

	AS		ET		EF I		EF II		LU		eL 12		eL 40		AU 10		AU 20		
	1 mm/2 mm ceramic		1 mm/2 mm ceramic		1 mm/2 mm ceramic		1 mm/2 mm ceramic		1 mm/2 mm ceramic		1 mm/2 mm ceramic		1 mm/2 mm ceramic		1 mm/2 mm ceramic		1 mm/2 mm ceramic		
AS	--	*	--	*	--	*	--	*	*	*	*	--	--	*	*	*	*	*	
ET	--	*	*	*	--	--	--	*	*	*	*	*	--	*	*	*	*	*	
EF I	*	*	*	*	*	*	--	*	*	*	*	*	--	*	*	*	*	*	with
EF II	*	*	--	*	--	*	*	*	*	*	*	--	--	--	*	*	*	*	self-curing
LU	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	--	*	catalyst
eL 12	*	*	*	*	*	*	*	*	*	*	*	*	*	--	--	*	*	*	
eL 40	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	
AU 10	*	*	*	*	*	*	*	*	--	*	--	--	*	*	--	--	*	*	
AU 20	*	*	*	*	*	*	*	*	*	*	*	*	--	*	*	*	--	*	

without self-curing catalyst

**=significant difference and -- = no significant difference at* p≤ *0.05*

Table 4: *Statistical Results of the Mann-Whitney-test: Pairwise Comparisons of Vickers Hardness on the 0.5/1.0 mm Composite Layer Under the 1 mm Ceramic Restoration*

	AS		ET		EF I		EF II		LU		eL 12		eL 40		AU 10		AU 20		
	0.5/1.0 mm layer		0.5/1.0 mm layer		0.5/1.0 mm layer		0.5/1.0 mm layer		0.5/1.0 mm layer		0.5/1.0 mm layer		0.5/1.0 mm layer		0.5/1.0 mm layer		0.5/1.0 mm layer		
AS	*	*	*	*	*	*	*	*	--	*	--	--	--	--	*	*	--	*	
ET	*	--	*	*	*	*	*	--	*	*	*	*	*	*	--	*	*	--	
EF I	*	*	*	*	*	*	--	*	*	*	*	*	--	*	*	*	*	*	with
EF II	--	*	*	*	--	*	*	*	*	--	*	*	*	*	*	*	*	*	self-curing
LU	*	--	*	*	*	--	*	*	*	*	*	*	*	*	*	*	*	*	catalyst
eL 12	*	*	*	*	*	*	*	--	*	*	*	*	*	--	*	*	*	*	
eL 40	*	--	*	*	*	*	*	*	--	*	*	*	*	*	*	*	*	*	
AU 10	*	*	--	*	*	*	*	*	*	*	*	*	*	*	*	*	*	--	
AU 20	*	*	*	--	*	--	*	*	--	*	*	*	--	*	*	*	*	*	

without self-curing catalyst

**=significant difference and -- = no significant difference at* p≤ *0.05*

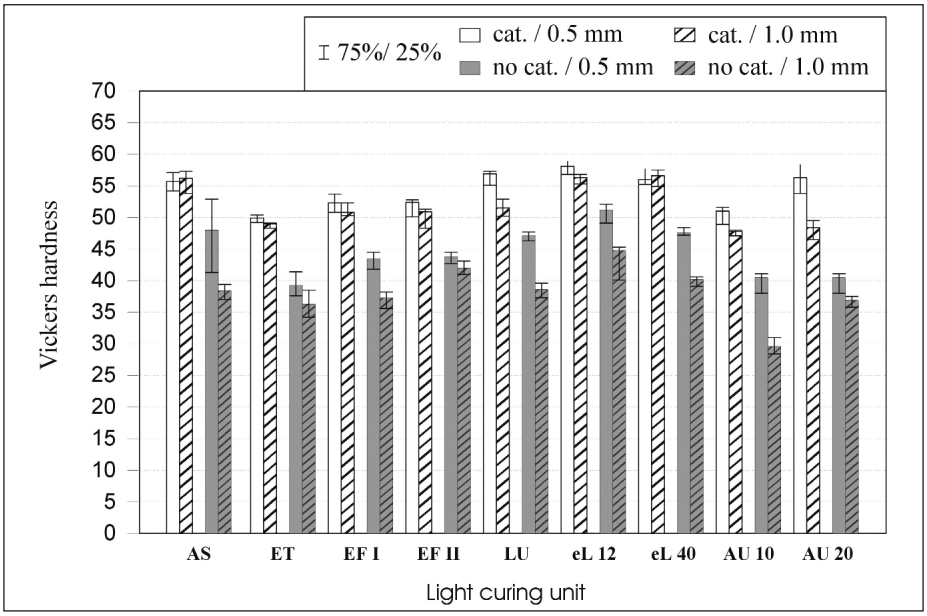

Figure 4: *Medians and 25/75 percentiles of the Vickers hardness of the resin composite luting material in different depths under the 1 mm ceramic restoration when used with and without self-curing catalyst with different polymerization modes.*

Mowafy & Rubo, 2000) that was not supported by the results of this study, where the use of a self-curing catalyst always produced higher hardness values with all polymerization modes. Additionally, with the exception of AU 10, the use of a self-curing catalyst always resulted in a greater depth of cure under 2-mm thick ceramic specimens. However, Breeding, Dixon and Caughman (1991) reported that chemical curing itself did not produce the extent of surface hardness that light curing did. In light-cured composites without the addition of a self-curing catalyst, a specific power density is required for a defined exposure duration to activate the maximum amount of initiator. After absorption of the necessary light quanta for decompensation of the initiator, the light apparently passes unimpeded (Harrington, Wilson & Shortall, 1996).

Table 5: *Statistical Results of the Mann-Whitney-test: Pairwise Comparisons of Vickers Hardness on the 0.5/1.0 mm Composite Layer Under the 2 mm Ceramic Restoration*

	AS		ET		EF I		EF II		LU		eL 12		eL 40		AU 10		AU 20		
	0.5/1.0 mm layer		0.5/1.0 mm layer		0.5/1.0 mm layer		0.5/1.0 mm layer		0.5/1.0 mm layer		0.5/1.0 mm layer		0.5/1.0 mm layer		0.5/1.0 mm layer		0.5/1.0 mm layer		
AS	*	*	*	*	*	*	*	*	*	--	*	*	--	*	*	*	*	*	
ET	*	*	*	*	--	--	*	--	*	--	*	*	*	--	--	--	--	*	
EF I	*	*	--	*	*	*	*	--	*	*	*	--	*	--	--	--	*	*	with
EF II	*	*	--	*	--	*	*	*	*	*	*	--	*	*	*	*	--	*	self-curing
LU	*	*	*	*	*	*	*	*	*	*	--	*	*	*	*	*	*	*	catalyst
eL 12	*	*	*	*	*	*	*	*	*	--	*	*	*	*	*	*	*	*	
eL 40	*	*	--	*	*	*	--	--	*	*	*	*	*	*	--	--	*	*	
AU 10	*	*	*	*	*	*	*	*	--	--	--	--	*	*	*	*	*	*	
AU 20	*	*	*	*	*	*	*	*	--	*	--	*	*	*	--	*	*	*	
without self-curing catalyst																			

**=significant difference and -- = no significant difference at p≤ 0.05*

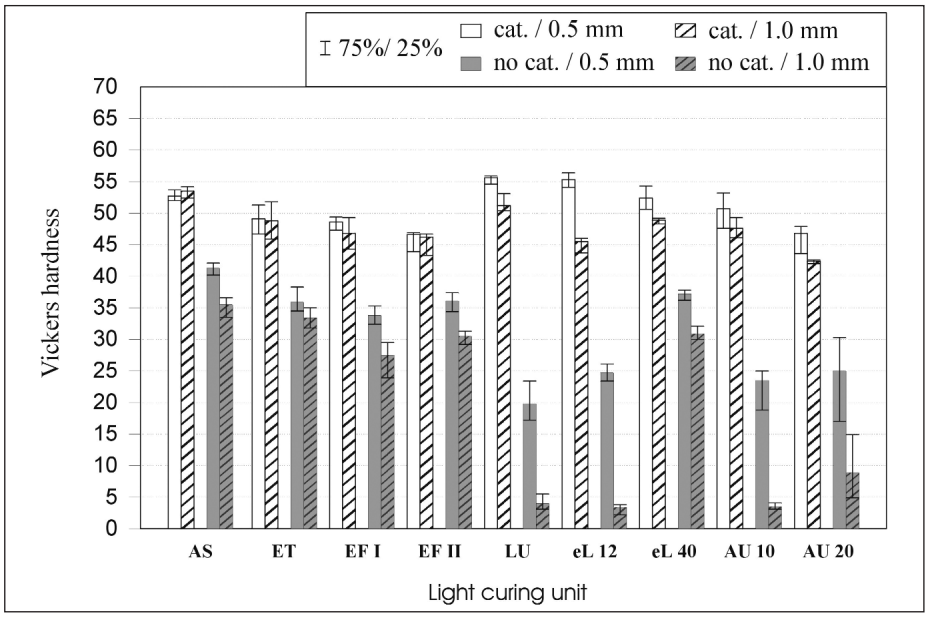

Figure 5: *Medians and 25/75 percentiles of the Vickers hardness of the resin composite luting material in different depths under the 2 mm ceramic restoration when used with and without self-curing catalyst with different polymerization modes.*

el-Mowafy and Rubo (2000) showed that even a 1-mm thick resin composite spacer considerably decreased light intensity by 70%. Beyond 1 mm, light intensity continued to decrease with increasing thickness of the spacer, with a total obstruction occurring at 4-mm thickness. This data was supported by the results of this study, where hardness values in the 0.5-mm deep composite layer were always significantly higher compared to the 1.0 mm layer, when no self-curing catalyst was used. An increase in thickness of the ceramic also resulted in significantly lower hardness, except for AS 20 in the 0.5-mm layer.

The depth of cure has been shown to increase proportionally to the logarithm of the product of light intensity and exposure duration (Chan & Boyer, 1989). Since conventional halogen curing units with light intensities of at least 400 mW/cm² and an exposure duration of 40 seconds have been shown to provide adequate composite cure (Rueggeberg & others, 1994), ET can be considered to be a standard in this study.

It is claimed that exposure duration can be reduced by half, compared to conventional halogen lamps, when using high power halogen units. This study showed that both depth of cure and hardness were equal or even higher for AS 20 compared to ET, a finding which was not supported by other studies where AS showed lower hardness values (Bouillaguet & others, 2003; Yap, Wong & Siow, 2003). However, in contrast to the current investigation, AS was not used in the mode of highest intensity output. In this turbo mode, the measured light intensity in this study differed considerably from the manufacturer. The occurrence of such a phenomenon was described earlier by Uhl and others (2003b), who reported on the light intensities of 1524 mW/cm² for the Elipar TriLight halogen curing unit. Those results may be explained by calculation of the influence of the light tip on power density as was done in both studies.

In this study, the LEDs LU and eL 12 showed the lowest depth of cure and hardness compared to other LED light-curing units and to ET, especially when used without a self-curing catalyst and under 2 mm of ceramic. This finding supports the results of Mills and others (2002), showing that LU reached inferior hard-

ness values in deep composite layers compared to a halogen curing unit and two high-power LEDs. The LU as used in this study had seven unmodified blue LEDs assembled into an array and was one of the first commercially available LEDs. The LED's poor performance can be explained by its relatively poor power density. It was reported that eL emitting 600 mW/cm^2 for 20 seconds was less effective than another LED (EF I) and a halogen curing unit (Soh & others, 2003; Asmussen & Peutzfeldt, 2003). The authors assumed that the fast cure mode as used in this study might have improved the results. However, the current investigation showed that eL 12 (fast cure mode) was also less effective compared to EF I and ET without the presence of the self-curing catalyst through 2 mm ceramics. A prolongation of the exposure duration to 40 seconds resulted in significantly higher values for both depth of cure and hardness for eL, although power density for eL 40 was much lower than for eL 12. In this context, the measured power density was much lower than the values supplied by the manufacturer. The LEDs eL 40 and EF I generated almost similar power densities and were used for the same exposure duration. Although depth of cure and hardness were significantly different under different conditions, the absolute differences were minimal.

The effectiveness of EF I in composite curing has been shown to be similar to a conventional halogen light curing unit (ET) (Soh & others, 2003). That finding was not corroborated in this study when evaluating results under the 2 mm ceramic discs, where depth of cure and composite hardness were significantly lower for EF I compared to ET, especially when no self-curing catalyst was used. These findings were also supported by Uhl and others (2003a) for depth of cure. They claimed that exposure duration had the greatest influence on depth of cure, followed by influence of the composite material and the selected light curing unit.

Thus, LED technology has advanced significantly and higher-power LEDs are increasingly available. In this study, depths of cure and hardness of EF II and ET were basically similar, which was in agreement with the findings of Ernst and others (2003).

In the literature, plasma-arc (PAC) lamps are often discussed as an alternative to high-power LED and high-power halogen light-curing units (Sfondrini, Cacciafesta & Klersy, 2002; Hadechney & others, 1999). However, this investigation showed that both depth of cure and hardness were significantly lower for both AU 10 and AU 20 compared to ET with composite used without a self-curing catalyst, especially under the 2 mm ceramic discs. Even a doubling of exposure duration was of minor influence. This result may have been caused by the special spectrum of this lamp, which, on the one hand, has very high light intensities at certain wavelengths, and on the other hand, are concentrated in very narrow peaks so that the initiator may not have been decomposed in the given time. Other studies (Jung & others, 2001; McLean & Fassbinder, 1999) also showed that the manufacturers' recommended exposure duration for PAC units may not be sufficient. Controversial results have been reported in the literature concerning the degree of conversion with PAC and halogen curing lights. Hadechney and others (1999) reported greater hardness with PAC, whereas Burgess and others (1999) showed that the Rockwell hardness after PAC exposure was significantly lower in 2-mm composite depth compared to conventional QTH curing. Burgess also showed that the degree of cure dropped significantly with the thickness of the composite layer (Burgess & others, 1999), which also was shown in the current study, although the PAC light used had a wider wavelength range (350-510 nm). Peutzfeldt and others (2000) reported reduced depth of cure and a lower flexural modulus resulting from a lower degree of conversion when a PAC unit was used. Poor mechanical properties correlate well with poor conversion caused by a high amount of unreached monomer (Asmussen, 1982a).

Since there are no commonly accepted requirements for effectiveness of light unit performance, the results of new polymerization techniques should be at least as good as those achieved with the "standard" halogen curing device. Under the experimental conditions of this study, eL 12, LU, AU 10 and AU 20 cannot be recommended for curing through ceramic restorations of more than 2-mm thickness.

CONCLUSIONS

Under the conditions of this *in vitro* study:

1. Increasing thickness of ceramic specimens had a negative effect on curing depth and hardness for all polymerization modes.
2. The effectiveness of LED units was very product-dependent.
3. Concerning AU, the special type of light spectrum may have been responsible for the unsatisfying results under 2-mm specimens when the resin composite was used without catalyst.
4. Inclusion of a self-curing catalyst always produced an equal or greater hardness and depth of cure with all polymerization methods.

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