THE EFFECT OF USING VARIABLE CURING LIGHT TYPES AND INTENSITIES ON THE PARAMETERS OF A MATHEMATICAL MODEL THAT PREDICTS THE DEPTH OF CURE OF LIGHT-ACTIVATED DENTAL COMPOSITES

by

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Submitted to the Graduate Faculty of the School of Dentistry in
partial fulfillment of the requirements for the degree of Master of Science
in Dentistry, Indiana University School of Dentistry, 2009.

Thesis accepted by the faculty of the Division of Prosthodontics, Department of Restorative Dentistry, Indiana University School of Dentistry, in partial fulfillment of the requirements for the degree of Master of Science in Dentistry.

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ACKNOWLEDGMENTS

It is an honor to thank the graduate Prosthodontic faculty at Indiana University School of Dentistry for all the knowledge and experience they passed on to me during the course of my study. Every one of you helped me learn a unique aspect of prosthodontics and your lessons will always be my keys to success in the future.

Special thanks to Dr. John Levon who acted as a brother and a dear friend to me before being a program director. His support and guidance helped me to defeat many challenges.

To Dr. Chu, my research mentor, I thank you and appreciate all the help and guidance you gave me throughout my study. Your knowledge and great spirit supported me in conducting and completing this research

I would like to extend my sincere appreciation to my research committee members, Dr. Andres, Dr. Brown, Dr. Hovijitra, and Mr. Eckert for their valuable guidance and help throughout my research.

To Ms. Meoghan MacPherson from the Dental Materials department, I deeply appreciate your remarkable help and support during the preparation and performance of my research. I wish you success and the best in life.

To my dear colleagues and classmates, I spent an important and valuable part of my life with you. I learned a lot from you, sometimes we agreed and other times we disagreed; but after all, I appreciate and respect all of you and wish success and happiness to all.

Finally, and most importantly, I have to thank my dear family for all the love, support, and patience they granted me during the course of my study.

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INTRODUCTION

Light activated resin composites are widely used in restorative dentistry today. Clinically, one of the major advantages of the photo-activated resins over the self or chemical cure resins is that the clinician controls the initiation of the polymerization reaction, thus, increasing the working time necessary for placing and contouring the material.

Many factors affect the degree of polymerization in light activated resin composites, such as the source light intensity, duration of exposure, material composition, shade, and translucency. Researchers have been studying the relative effect of these factors on the kinetics of polymerization and a number of studies provided mathematical models to predict the degree of polymerization and depth of cure in light activated resin composites.

A simple mathematical model that predicts the depth of cure was proposed by Jacobs[1] as: $Cd = D_p \, In(E_0/E_c)$ where Cd is the depth of cure of the polymer, E_o is the input energy at the surface of the resin, E_c is the minimum exposure required to allow the polymer to reach its gel point, and D_p is a material dependent and wavelength dependent characteristic length and is defined as the resin penetration depth at a particular wavelength. It is a characteristic coefficient with a unit of millimeter that accounts for the solid volume ratio, the particle size, the scattering effect, and the absorption coefficient of the composite.

In a previous study, Katsilieri[2] has demonstrated that this mathematical model can fully describe the logarithmic relation between the output energy of a halogen dental curing unit and the DOC of three different VLDC's with three different shades. The two parameters needed to describe the relation between DOC and input energy was identified for each composite. A statistical protocol was further developed to statistically analyze the differences in these two curing parameters between different composites. However, whether this equation will apply to the DOC obtained from other light sources is still unknown.

The purpose of this study is to further investigate the effect of using different light source types with different light output intensities on the parameters of this mathematical model $D = D_p \text{In}(E_0/E_c)$ which predicts the depth of cure in visible light dental composites (VLDC's);

Where:

D is the depth of cure in millimeters,

E is the curing energy in J/cm^2,

E_c is the critical curing energy for the composite to reach a gel layer, and

D_p is a characteristic coefficient with a unit of millimeter that accounts for the solid volume ratio, the particle size, the scattering effect, and the absorption coefficient of the composite.

The D_p and E_c curing parameters obtained for each composite under different curing lights will be statistically compared by Boot-Strap analysis described in the statistical analysis part of the results section.

The null hypothesis of this study is that using different light source types with different light output intensities will not significantly affect the parameters of the proposed mathematical model $D = D_p \text{In}(E_0/E_c)$ calculated from the experimental data obtained by the scraping technique (DOC) versus the curing energy (in logarithmic scale).

REVIEW OF LITERATURE

MATHEMATICAL MODELS IN THE LITERATURE

Throughout the literature, many mathematical models were developed to describe the relationship between the polymerization behavior of VLDC's and the factors affecting this behavior. In those studies, experimental data describing the depth of cure of VLDC's were obtained by variable techniques such as ISO scraping technique, Knoop hardness testing, and IR spectroscopy and were compared to the proposed models. The significance of those models is to assess the quantitative effect of the different factors on polymerization kinetics of VLDC's.

Wayne D. Cook[3] proposed a theoretical inhibition model for polymerization in which the depth of cure (D) was linear with $\log_{10}$ the irradiation time (t) with a slope of (1/ε), where (ε) is the absorption co-efficient of the composite material. $D = 1/\varepsilon \log_{10} [(2.303\ K_1\ Ø\ I_0\ \varepsilon_s\ S\ t)\ (K_2\ K_3\ X_0)]$

Cohen et al.[4] used a non linear regression to support the fit of the experimental data to the model $Y = Y_{max}(1\text{-}e^{-kt})$, where Y is the observed hardness, Y_{max} is maximum hardness, t is the exposure duration, and k is a rate parameter indexing how quickly the Y_{max} is approached. This model described the sub-surface resin polymerization sufficiency by measuring bottom to top surface Knoop hardness ratios.

Chen et al.[5] used the Monte Carlo simulation, which describes the radiant exposure distribution (H) in a composite material, to predict the extent of cure (DC). The relationship between (DC) and (H) fitted both the exponential model $DC = DCmax[1\text{-}\exp((\text{In } 0.5)H/H_{dc}^{50\%})]$ and the Racz's model $DC = DCmax/[1+(H/H_{dc}^{50\%})^{-2}]$, where

$H_{dc}^{50\%}$ is a fitting parameter representing the threshold for 50 percent of the maximum curing level.

Emami et al.[6] relied on the Beer-Lambert's law to determine the effect of different factors such as filler type, filler surface treatment, and light source on light attenuation in visible light cured dental composites. A linear model was statistically proved to work well in describing the changes in absorbance as either filler fraction or sample thickness changes: $\mathrm{In}(P/P_0) = -(\alpha_a + \alpha'_a + \alpha_s)d + (\alpha'_a - \alpha'_s) V_f d + \mathrm{In}(1-R_f)$ or $Z = A + Bd + CdV_f$, where Z is the initial optical power, A is reflection term, B is absorption pluss scattering factor, α is the attenuation coefficient, C is a factor showing the difference between higher order absorption and scattering terms, and d is the thickness of the sample.

Rueggeberg et al.[7] studied the relative effect of exposure duration, light intensity, filler type, and shade on percent-monomer conversion, and the experimental results agreed to the proposed mathematical model: $C = -39.9 + 56.4(\log D) - 10.3(T^2) - 0.5(F) + 51.7(\log I) + 2.6(\log I)(\log D)(T^2) - 29.7(\log I)(\log D)$, where C = percent-monomer conversion, D is duration of exposure, T^2 is thickness of overlying resin composite in mm^2, F = type of filler (1-hybrid, 2-micorfill), and I is source intensity in mW/cm^2.

The mathematical model in this study was first proposed by Jacobs[1] as $Cd = Dp\mathrm{In}(E_o/Ec)$ and was derived from the Beer-Lambert law: $E_{(Z)} = E_0 \exp(-z/D_p)$ where $E_{(Z)}$ is the energy at depth below the surface of the resin, E_0 is the input energy at the surface of the resin, and D_p is a material and wavelength dependent and is defined as the resin penetration depth at a particular wavelength. This model shows a linear relationship between the depth of cure (Cd) of a polymer and the natural logarithm of input energy (E_0) at the surface of the resin.

METHODS FOR MEASURING DEPTH OF CURE (DOC)

IR SPECTROSCOPY

This technique is based on the fact that Functional groups in molecules absorb electromagnetic radiation in the IR region, and can be identified according to the IR absorption bands. Infrared spectroscopy measures the degree of conversion from the intensities ratio of the aliphatic to aromatic stretching vibrations. A number of formulas have been used to calculate the aliphatic to aromatic C = C conversion degree based on this technique. A simplified formula was reported by Ferracane and Greener[8]:
% Conversion = (1-C/U) X 100%, where C is the equivalent molar ratio of the cured specimen; U is the equivalent molar ratio of the uncured specimen. Measuring the degree of C = C conversion using the IR spectroscopy is considered to be a highly accurate and reliable technique in determining the depth of cure of light cured resin composites.

KNOOP MICRO-HARDNESS TEST

This technique is one of the most extensively used methods in depth of cure studies due to the accuracy and simplicity of the technique. It involves a static indentation made by a Knoop elongated diamond pyramid and with a load not exceeding 1 kgf. The tested surface requires a metallographic finish and a precision microscope is used to measure the indentations. The Knoop hardness number (KHN) is the ratio of the load applied to the indenter P (Kgf) to the unrecovered projected area A (mm^2): KHN = F/A = P/CL^2, where F is the applied load in (Kgf), A is the unrecovered projected area of the indentation in (mm^2), L is the measured length of the long diagonal of the indentation in (mm), and C = 0.07028, is the constant of the indenter relating the projected area of the indentation to the square of the length of the long diagonal[9].

ISO SCRAPING TECHNIQUE

This technique is considered to be one of the simplest methods to determine the depth of cure in resin composites and was adopted in the ISO-norm 4049:2000(E).[10] It consists of scraping away the underlying soft paste then measuring the remaining thickness of the sample and dividing that by two to get the depth of cure (DOC). The divided by two depth roughly corresponds to 80-percent polymerization of the polymer which provides sufficient strength to the material. Even though, the scraping technique tends to overestimate the curing depth of resin composites when compared to other methods like the Knoop hardness or IR spectroscopy, it allows a comparison of the curing depth of materials.[11] The depth of cure as measured from the scraping technique is slightly higher than the other popular methods like the Knoop micro-hardness or IR spectroscopy, thus the statement of overestimation is seen in the literature. However, the scraping method has a stronger photo-physics and photochemistry theory basis than the other techniques. Moreover, the scraping technique is the standard method of choice to evaluate the polymerization behavior in terms of the depth of cure as listed in the ADA specification. We thus choose to use it in this study.

THE EFFECT OF CURING LIGHT SOURCE ON THE DEPTH OF CURE IN VLDC's

Several studies investigated the effects of curing light properties on the depth of cure in VLDC's. These properties included the type of light used, output intensity, energy density, wavelength spectral distribution, and light attenuation within the bulk of the cured composite material. The curing mode was also analyzed in several studies to identify any possible effects on the curing effectiveness and depth of cure.

Soh et al.[12] compared the curing effectiveness of halogen and LED curing lights with different curing regimes. The LED curing lights were found to have narrower spectral distribution that lies within the absorption spectrum of camphorquinone (CQ) photo-initiator which is 450-500 nm with peak absorption at 470 nm. Theoretically, this would mean that LED curing lights would induce a more effective resin polymerization, but there are other factors that control this process. In this study, it was concluded that at the surface and up to 2 mm depth, all the curing lights with different curing modes meet the minimal required hardness ratio in resin composites. As the light passes through the bulk of the cured material, its intensity usually decreases due to absorption and scattering by the resin material. Therefore, the output intensity was found to have more significant effects on the polymerization kinetics at depths greater than 2 mm.

In a study by Nomoto,[13] it was confirmed that in the 450-490 nm wavelength range, the polymerization and depth of cure of VLDC’s would primarily be affected by the exposure energy rather than the light wavelength. However, in other ranges, the wavelength might have a more dominant effect over the exposure energy regarding the polymerization and depth of cure of VLDC’s.

In a study by Rueggeberg and Jordan,[14] they found that the polymerization on the surface of VLDC’s is greatly dependent on exposure duration and that the output intensity would start to have a significant effect at 2 mm below the composite surface. They also analyzed the effect of light tip distance on the polymerization behavior and found that a distance of more than 4 mm from the resin surface demonstrated a significant decrease in resin polymerization 2 mm below the resin composite surface. Moreover, they reported that the use of high intensity light sources improves the physical and mechanical properties of the cured restorative material due to increasing the degree of conversion and depth of cure in that material.

Miyazaki et al.[15] confirmed that the polymerization process depends on the total exposed light energy (intensity x time) rather than the light intensity alone, and that the effectiveness of cure depends on energy density.

Cunha et al.[16] performed a comparative analysis study between different photo-activation methods including the continuous, stepped, intermittent, and plasma arc methods concerning superficial and bottom hardness. The continuous and the stepped methods didn't significantly differ from each other at any of the analyzed area's and both of them presented higher values than the intermittent curing method. The plasma arc method was only statistically different from the continuous and stepped methods at depths below 2.5 mm where significant decrease in the hardness was observed.

Leonard et al.[17] compared the curing efficiency of three LED curing lights to a quartz tungsten halogen (QTH) light using the hardness testing. Even though the halogen light had a broader spectral emission and a smaller percentage of their power density fell within the 450-500 nm absorption range of the camphorquinone, it was still at least four times more powerful than the LED lights. Consequently, the LED lights required longer exposure duration for adequate polymerization.

Moreover, several studies have concluded that the effect of light type by itself, whether LED or halogen, is not significant on the depth of cure of VLDC's.[18-20]

However, in these studies, the interaction of light type with other factors like exposure duration or shade presented significant affects on the depth of cure of VLDC’s.

MATERIALS AND METHODS

This study is performed in a laboratory setting and the experiment is based on measuring the depth of cure for of the resin composite specimens in relation to the amount of curing light energy applied to these specimens by different light sources.

SAMPLE PREPARATION

Three shades (A3, B1, D3) of a hybrid resin (Table I) (AELITE All Purpose Body, BISCO Inc., Schaumburg, IL) composite were used to prepare the specimens for this study (Figure 1). A Teflon® mold with 4 X 6 mm holes (Figure 2) was used to prepare the composite specimens. Mylar® sheets were placed at the top and bottom of the holes after they were filled with the composites. Finger pressure against glass slides on the top of the Mylar® sheets was applied to remove excess material. A metal sheet (1mm thickness) was screwed on the top of the Teflon® mold and it contains 4mm holes corresponding to top surface of the composites. Using the metal sheet on top of the Teflon® mold was to compensate for any size differences in the curing light guides because the holes in the metal sheet are of a fixed diameter, 4mm.

Three LED and three halogen dental curing units with different light output intensities (Table II) were used to cure the three shades (B1, A3, D3) of the composite specimens. Each curing unit- shade combination was cured for 10, 20, 30, and 40 seconds. Based on the previous study done by Katsilieri,[2] It was not needed to extend the curing duration beyond 40 seconds since the curing relation holds for longer curing times. So, the same protocol in Katsilieri’s study regarding the curing duration has been followed in my study since the focus of my study is to investigate the effect of using different curing light output intensities. Also, three samples were obtained for each shade-irradiation time combination.

During the fabrication of the resin samples, the output intensity of each curing light was measured in mW/cm^2 using the Cure Rite Visible Curing Light Meter (DENTSPLY/Caulk, Milford DE) before and after making each shade-light combination group of samples. The before and after readings were averaged for each sample group and that output intensity average was used to calculate the output energy in each shade-light combination group. The metal sheet “1mm thickness” that goes on top of the Teflon® mold was held against the radiometer so that the 4mm hole of the metal sheet matched the center of the radiometer sensor cell. The curing light tip was held against the metal sheet, so that the output intensity was measured through the metal sheet which is 1mm thick and that is the distance between the tip of each curing light and the top surface of composite sample in the Teflon® mold hole.

When the B1 shade samples were prepared, the majority of the samples cured to the full depth of the Teflon® mold. To avoid any false results, it was decided to remake all the B1 shade samples and a deeper Teflon® mold (4 X 12) was used for that purpose.

The halogen lights (Figures 3-5) and their corresponding measured output intensities are: Optilux VCL 401 Curing-Light (Kerr Dental) with 270 mW/cm^2, Elipar High light (3M/ESPE, St. Paul, MN) with 430 mW/cm^2, and Astralis 5 (Ivoclar Vivadent, Amherst, NY**)** with 255 mW/cm^2 (Figures 1 through 6). The LED units (Figures 4-6) are: Visilux 2 (3M/ESPE) with 350 mW/cm^2, Demi (Kerr Dental) with 540 mW/cm^2, and Allegro (Den-Mat, Santa Maria, CA**)** with 350 mW/cm^2. These are the initial testings performed for each of the curing lights using the radiometer with the metal sheet in the middle as described previously.

ISO SCRAPING TEST

A plastic spatula was used to remove any soft composite from the end of the specimens. The remaining length of the specimen was measured by a digital micrometer (Digimatic Caliper model CD-6BS, Mitutoyo Corp., Aurora, IL) of 0.01 mm accuracy, and 3 measurements were obtained for each specimen. The mean average of each specimen was divided by two to calculate the depth of cure (DOC)[1].

RESULTS

The results of the ISO scraping technique: depth of cure (DOC) vs. the curing energy (in a logarithmic scale) were plotted for all the light source-shade combinations. The non-linear equation DOC = $D_p \ln(E_0/E_c)$ was used to define the relationship between exposure and DOC. The values for D_p and E_c were estimated for each of the eighteen shade-light combinations using non-linear regression models (Table III). Comparisons between regression lines were performed using F-tests to determine if the (D_p, E_c) pairs were significantly different for each pair of shade-light combinations. Additional tests were performed to compare the individual D_p and E_c estimates using bootstrap sampling. Bootstrap sampling can be used to estimate parameters and their standard errors when direct estimates are not easily computed.[21] Sampling was performed 1000 times with replacement from the original data, the non-linear regression analyses were performed within each sample, and the results from the 1000 samples were combined to obtain empirical distributions of the differences in D_p and E_c between each pair of shade-light combinations. The means, standard errors, and p-values were then estimated to compare the shade-light combinations.

Under the different curing lights, the D_p values ranged from 0.45 to 0.54 for A3, from 0.91 to 1.05 for B1, and from 0.47 to 0.55 for D3. The E_c values ranged from 50.8 to 186.7 for A3, from 122.4 to 355.2 for B1, and from 68.9 to 217.3 for D3 (Table IV). A3, B1, and D3 had significantly different regression lines for Allegro, with significantly higher D_p for B1 than A3 and D3. A3, B1, and D3 had significantly different regression lines for Astralis 5 and Visilux 2 with significantly higher D_p for B1 than A3 and D3 and significantly higher E_c for B1 than A3. A3, B1, and D3 had significantly different regression lines for Demi, with significantly higher D_p and E_c for B1 than A3 and D3. B1 had significantly different regression lines than A3 and D3 for Elipar High Light and Optilux, with significantly higher D_p and E_c for B1 than A3 and D3.

For shade A3, Allegro and Demi did not have significantly different regression lines, and Astralis 5 and Elipar High Light did not have significantly different regression lines. The detailed comparisons indicated significantly higher D_p for Demi and Visilux 2 than for Astralis 5 and Elipar High Light; significantly lower E_c for Elipar High Light and Astralis 5 than Demi and Visilux 2; and significantly lower Allegro than Visilux 2 (Table V).

For shade B1, Allegro and Astralis 5 did not have significantly different regression lines, and Elipar High Light and Visilux 2 did not have significantly different regression lines. The detailed comparisons indicated significantly lower D_p for Allegro and Astralis 5 than for Demi, Optilux, and Visilux 2; significantly lower E_c for Allegro and Astralis 5 than for Demi, Elipar High Light, Optilux, and Visilux 2; and significantly lower E_c for Demi than for Optilux (Table VI).

For shade D3, Allegro and Demi did not have significantly different regression lines, and Astralis 5 and Elipar High Light did not have significantly different regression lines. The detailed comparisons indicated significantly higher E_c for Visilux 2 than for Allegro, Astralis 5, Demi, Elipar High Light, and Optilux; but no significant differences for D_p (Table VII).

Overall, the results of this study confirm that the shade factor has a more dominant effect on the depth of cure in VLDC's. Although, most of the significant effects on the D_p and E_c parameters occurred in the B1 shade-light combination, both parameters didn't show significant differences between A3 and D3 shades in all the groups (Table VIII). Also, most of the significant differences for D_p values occurred in the B1 shade-light combinations. However, none of the D3 shade-light combinations showed significant differences for D_p.

TABLES AND FIGURES

Table I

Material information as reported by manufacturer

Product Name & Manufacturer	Material Composition & Concentration Range %	Shade	Lot #
AELITE ALL PURPOSE BODY/ BISCO INC.	Ethoxylated Bis-GMA <30% Triethyleneglycol Dimethacrylate <20% Glass Filler <80% Amorphous Silica <15%	B1	0800008013
		A3	0800007718
		D3	0800004849

Table II

Dental curing units

Unit Name	**Light Type**	**Manufacturer/ Vendor**	**Measured Output intensity- mW/cm^2**
Optilux VCL 401	Halogen	Kerr Dental	270
Elipar High light	Halogen	3M/ESPE	430
Astralis 5	Halogen	Ivoclar Vivadent	255
Visilux 2	LED	3M/ESPE	350
Demi	LED	Kerr Dental	540
Allegro	LED	Den-Mat	350

Table III

The a and b values for the different light-shade combination regression lines represented by the mathematical model: Y=a * ln(x)-b

	B1		A3		D3	
	a	b	a	b	a	b
Optilux	1.1382	6.6845	0.5361	2.4491	0.4891	2.0704
Elipar	1.0223	5.7548	0.4473	1.7667	0.4844	2.1516
Astralis5	0.9082	4.3664	0.4532	1.7796	0.4737	2.0228
Visilux2	1.0512	5.9991	0.5421	2.8352	0.5473	2.9449
Demi	1.0512	5.8305	0.5297	2.6062	0.4572	2.0213
Allegro	0.9261	4.4845	0.4761	2.0888	0.4663	2.092

Table IV

D_p and E_c values for each shade-light combination

		D_p				E_c			
				Approximate 95% CI				Approximate 95% CI	
Shade	Light	Estimate	SE			Estimate	SE		
A3	Allegro	0.48	0.02	0.42	0.53	80.4	18.6	38.9	121.9
	Astralis 5	0.45	0.03	0.40	0.51	50.8	13.3	21.1	80.4
	Demi	0.53	0.03	0.47	0.59	137.1	33.6	62.1	212.0
	Elipar High Light	0.45	0.03	0.37	0.52	51.9	20.2	6.9	97.0
	Optilux	0.54	0.04	0.45	0.62	96.4	28.0	33.9	158.9
	Visilux 2	0.54	0.02	0.49	0.59	186.7	29.1	121.9	251.5
B1	Allegro	0.93	0.05	0.81	1.04	126.8	29.2	61.8	191.7
	Astralis 5	0.91	0.07	0.75	1.06	122.4	35.9	42.5	202.4
	Demi	1.05	0.04	0.97	1.13	256.3	33.2	182.4	330.2
	Elipar High Light	1.02	0.06	0.89	1.16	278.4	59.5	145.9	411.0
	Optilux	1.14	0.04	1.06	1.22	355.2	32.3	283.2	427.2
	Visilux 2	1.05	0.03	0.98	1.12	300.9	28.5	237.3	364.4
D3	Allegro	0.47	0.02	0.42	0.52	88.8	19.8	44.7	132.8
	Astralis 5	0.47	0.03	0.40	0.55	71.6	22.5	21.3	121.8
	Demi	0.46	0.04	0.37	0.54	83.2	34.8	5.5	160.8
	Elipar High Light	0.48	0.05	0.38	0.59	84.9	39.4	-2.8	172.7
	Optilux	0.49	0.03	0.42	0.56	68.9	18.9	26.9	111.0
	Visilux 2	0.55	0.03	0.47	0.62	217.3	47.7	110.9	323.6

TABLE V

Comparisons between A3 shade-light combinations

Comparison					D_p			E_c			Overall p-value
					Difference	SE	p-value	Difference	SE	p-value	
A3	Allegro	vs	A3	Astralis 5	0.03	0.04	0.3960	35.6	25.2	0.1569	0.0001
A3	Allegro	vs	A3	Demi	-0.05	0.04	0.1639	-57.4	42.5	0.1769	0.1986
A3	Allegro	vs	A3	Elipar High Light	0.04	0.04	0.3310	34.8	25.5	0.1727	0.0319
A3	Allegro	vs	A3	Optilux	-0.06	0.05	0.2258	-19.2	42.5	0.6526	<0.0001
A3	Allegro	vs	A3	Visilux 2	-0.06	0.03	0.0566	-106.0	38.9	0.0065	<0.0001
A3	Astralis 5	vs	A3	Demi	-0.08	0.04	0.0474	-93.0	40.4	0.0212	<0.0001
A3	Astralis 5	vs	A3	Elipar High Light	0.01	0.04	0.8692	-0.9	19.6	0.9646	0.2857
A3	Astralis 5	vs	A3	Optilux	-0.09	0.05	0.0810	-54.8	38.9	0.1592	0.0369
A3	Astralis 5	vs	A3	Visilux 2	-0.10	0.04	0.0120	-141.6	35.6	<.0001	0.0001
A3	Demi	vs	A3	Elipar High Light	0.09	0.05	0.0452	92.2	40.5	0.0229	0.0058
A3	Demi	vs	A3	Optilux	-0.01	0.06	0.8615	38.2	53.9	0.4779	<0.0001
A3	Demi	vs	A3	Visilux 2	-0.01	0.04	0.7635	-48.6	51.1	0.3414	0.0001
A3	Elipar High Light	vs	A3	Optilux	-0.10	0.06	0.0689	-53.9	38.7	0.1633	0.0014
A3	Elipar High Light	vs	A3	Visilux 2	-0.10	0.04	0.0167	-140.7	37.1	0.0001	<0.0001
A3	Optilux	vs	A3	Visilux 2	0.00	0.05	0.9615	-86.8	48.1	0.0713	<0.0001

TABLE VI

Comparisons between B1 shade-light combinations

Comparison					D_p			E_c			Overall p-value
					Difference	SE	p-value	Difference	SE	p-value	
B1	Allegro	vs	B1	Astralis 5	0.01	0.08	0.8521	1.5	38.3	0.9690	0.6948
B1	Allegro	vs	B1	Demi	-0.13	0.06	0.0191	-131.9	34.8	0.0002	<0.0001
B1	Allegro	vs	B1	Elipar High Light	-0.09	0.08	0.2296	-144.4	55.9	0.0098	<0.0001
B1	Allegro	vs	B1	Optilux	-0.21	0.07	0.0013	-228.2	47.4	<.0001	<0.0001
B1	Allegro	vs	B1	Visilux 2	-0.13	0.06	0.0228	-177.3	40.8	<.0001	<0.0001
B1	Astralis 5	vs	B1	Demi	-0.14	0.07	0.0367	-133.4	40.4	0.0010	0.0031
B1	Astralis 5	vs	B1	Elipar High Light	-0.10	0.08	0.2147	-145.9	59.3	0.0139	<0.0001
B1	Astralis 5	vs	B1	Optilux	-0.23	0.08	0.0038	-229.7	52.0	<.0001	<0.0001
B1	Astralis 5	vs	B1	Visilux 2	-0.14	0.07	0.0373	-178.8	44.6	<.0001	<0.0001
B1	Demi	vs	B1	Elipar High Light	0.04	0.07	0.5486	-12.5	57.9	0.8290	0.0002
B1	Demi	vs	B1	Optilux	-0.08	0.06	0.1331	-96.4	48.2	0.0457	0.0412
B1	Demi	vs	B1	Visilux 2	0.00	0.04	0.9960	-45.4	41.7	0.2761	<0.0001
B1	Elipar High Light	vs	B1	Optilux	-0.12	0.08	0.1058	-83.8	66.8	0.2096	0.0203
B1	Elipar High Light	vs	B1	Visilux 2	-0.04	0.07	0.5530	-32.9	61.9	0.5951	0.8051
B1	Optilux	vs	B1	Visilux 2	0.08	0.06	0.1322	51.0	51.4	0.3219	0.0046

TABLE VII

Comparisons between D3 shade-light combinations

Comparison					D_p			E_c			Overall p-value
					Difference	SE	p-value	Difference	SE	p-value	
D3	Allegro	vs	D3	Astralis 5	-0.01	0.04	0.8714	18.9	36.5	0.6035	<0.0001
D3	Allegro	vs	D3	Demi	0.02	0.05	0.7338	10.7	45.9	0.8155	0.8584
D3	Allegro	vs	D3	Elipar High Light	-0.01	0.05	0.7974	7.4	43.2	0.8643	0.0018
D3	Allegro	vs	D3	Optilux	-0.02	0.04	0.6610	24.6	34.4	0.4740	<0.0001
D3	Allegro	vs	D3	Visilux 2	-0.08	0.04	0.0710	-128.6	60.7	0.0341	<0.0001
D3	Astralis 5	vs	D3	Demi	0.02	0.06	0.6559	8.2	41.1	0.8410	0.0009
D3	Astralis 5	vs	D3	Elipar High Light	-0.01	0.05	0.9077	-11.6	39.6	0.7704	0.6075
D3	Astralis 5	vs	D3	Optilux	-0.01	0.04	0.7961	5.6	27.7	0.8441	0.0057
D3	Astralis 5	vs	D3	Visilux 2	-0.07	0.05	0.1231	-147.6	58.5	0.0116	<0.0001
D3	Demi	vs	D3	Elipar High Light	-0.03	0.06	0.6131	3.3	46.5	0.9432	0.0045
D3	Demi	vs	D3	Optilux	-0.04	0.05	0.5101	-13.9	38.3	0.7168	<0.0001
D3	Demi	vs	D3	Visilux 2	-0.10	0.06	0.0952	-139.3	64.2	0.0301	0.0040
D3	Elipar High Light	vs	D3	Optilux	-0.01	0.05	0.9210	17.2	37.5	0.6466	0.0038
D3	Elipar High Light	vs	D3	Visilux 2	-0.07	0.05	0.2177	-136.0	61.8	0.0277	<0.0001
D3	Optilux	vs	D3	Visilux 2	-0.06	0.05	0.1818	-153.2	55.8	0.0060	<0.0001

TABLE VIII

Comparisons between shade-light combinations

Comparison					D_p			E_c			Overall p-value
					Difference	SE	p-value	Difference	SE	p-value	
A3	Allegro	vs	B1	Allegro	-0.441	0.05	<.0001	-41.4	31.5	0.1888	<0.0001
A3	Allegro	vs	D3	Allegro	0.01	0.03	0.7580	-8.7	36.0	0.8098	0.0002
B1	Allegro	vs	D3	Allegro	0.45	0.05	<.0001	32.7	37.6	0.8852	<0.0001
A3	Astralis 5	vs	B1	Astralis 5	-0.46	0.07	<.0001	-75.5	33.8	0.0254	<0.0001
A3	Astralis 5	vs	D3	Astralis 5	0.03	0.04	0.5064	25.4	26.1	0.3314	0.0222
B1	Astralis 5	vs	D3	Astralis 5	0.13	0.07	<.0001	50.2	38.8	0.1962	<0.0001
A3	Demi	vs	B1	Demi	-0.52	0.04	<.0001	-115.9	45.8	0.0114	<0.0001
A3	Demi	vs	D3	Demi	0.08	0.05	0.1374	59.4	50.2	0.2365	0.0021
B1	Demi	vs	D3	Demi	0.60	0.06	<.0001	175.3	43.0	<.0001	<0.0001
A3	Elipar High Light	vs	B1	Elipar High Light	-0.57	0.07	<.0001	-220.5	53.1	<.0001	<0.0001
A3	Elipar High Light	vs	D3	Elipar High Light	-0.04	0.05	0.4529	-36.1	35.9	0.3155	0.2956
B1	Elipar High Light	vs	D3	Elipar High Light	0.53	0.07	<.0001	184.5	59.7	0.0020	<0.0001
A3	Optilux	vs	B1	Optilux	0.60	0.06	<.0001	250.5	55.2	<.0001	<0.0001
A3	Optilux	vs	D3	Optilux	0.05	0.05	0.3192	35.1	40.9	0.3916	0.3154
B1	Optilux	vs	D3	Optilux	0.65	0.06	<.0001	285.5	44.8	<.0001	<0.0001
A3	Visilux 2	vs	B1	Visilux 2	-0.51	0.04	<.0001	-112.7	46.1	0.0144	<0.0001
A3	Visilux 2	vs	D3	Visilux 2	0.00	0.04	0.9192	-81.8	64.5	0.6272	0.0213
B1	Visilux 2	vs	D3	Visilux 2	0.50	0.05	<.0001	81.3	63.1	0.1971	<0.0001

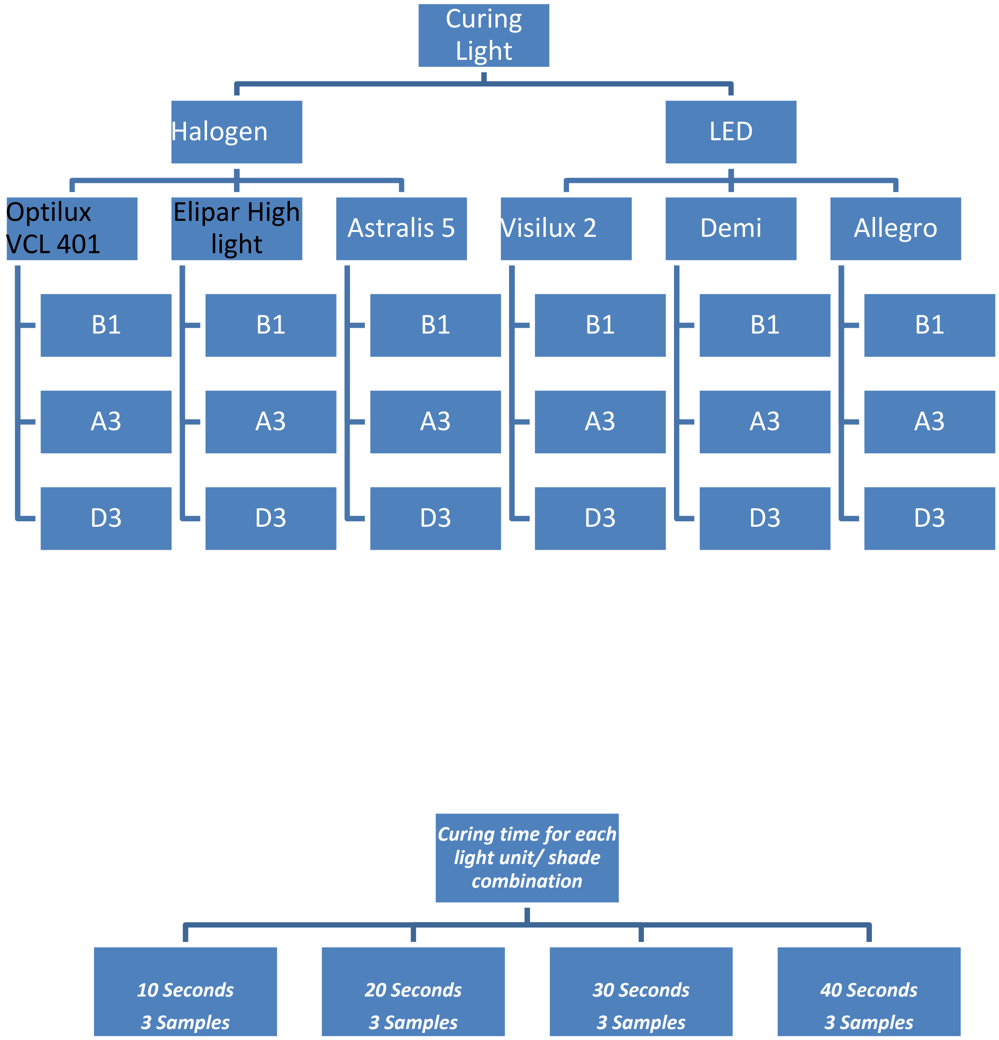

Figure 1. Experiment Design

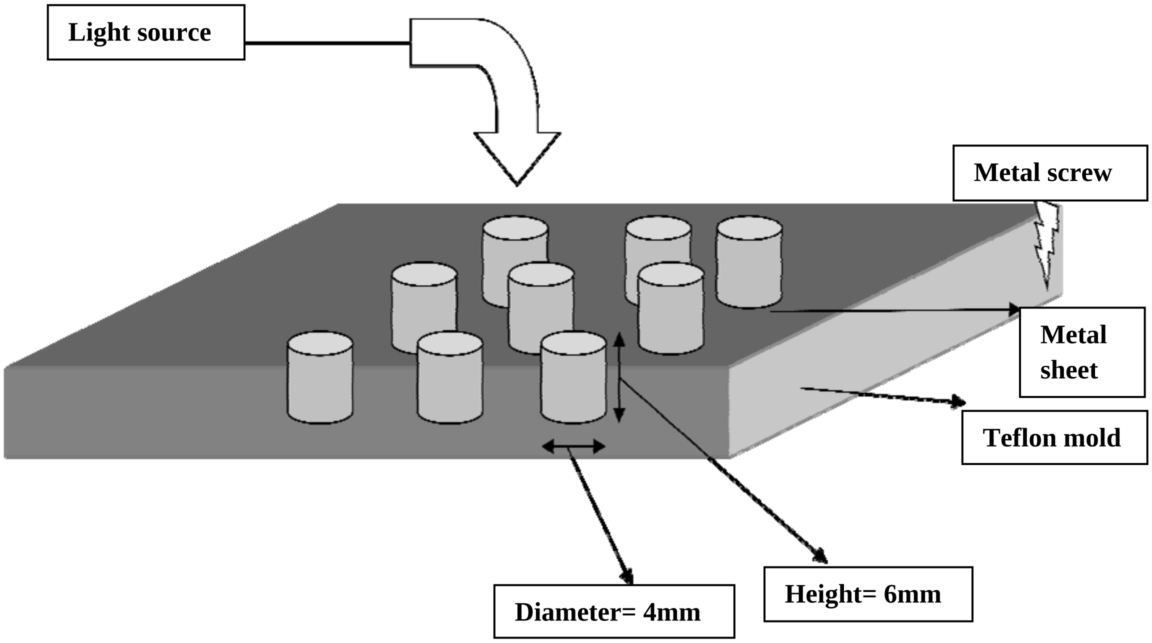

Figure 2. Sample preparation assembly

Figure 3 Optilux Light

Figure 4 Elipar H. Light

Figure 5. Astralis 5 Light 1

Figure 6. Visilux 2 Light

Figure 7. Illustration of Demi Light from www.Kerr.com

Figure 8. Allegro light

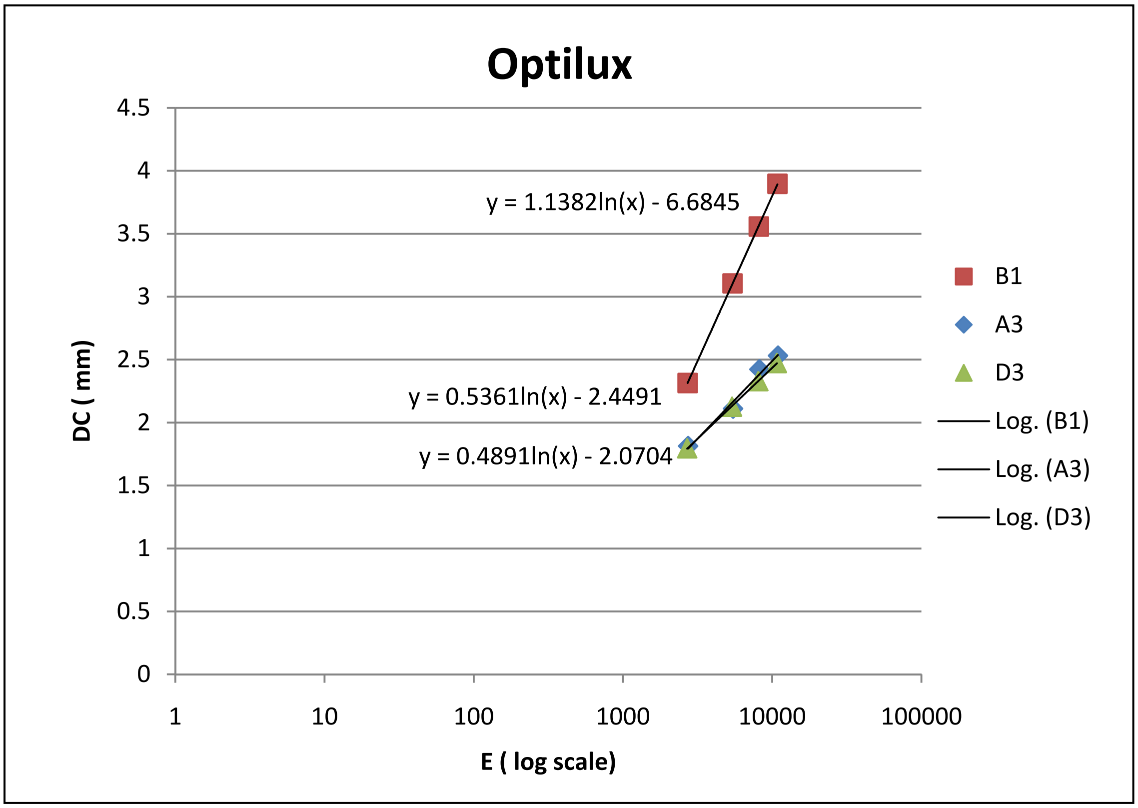

Figure 9. Regression lines of the different resin shades cured under Optilux light: Output energy in logarithmic scale vs. depth of cure in mm's.

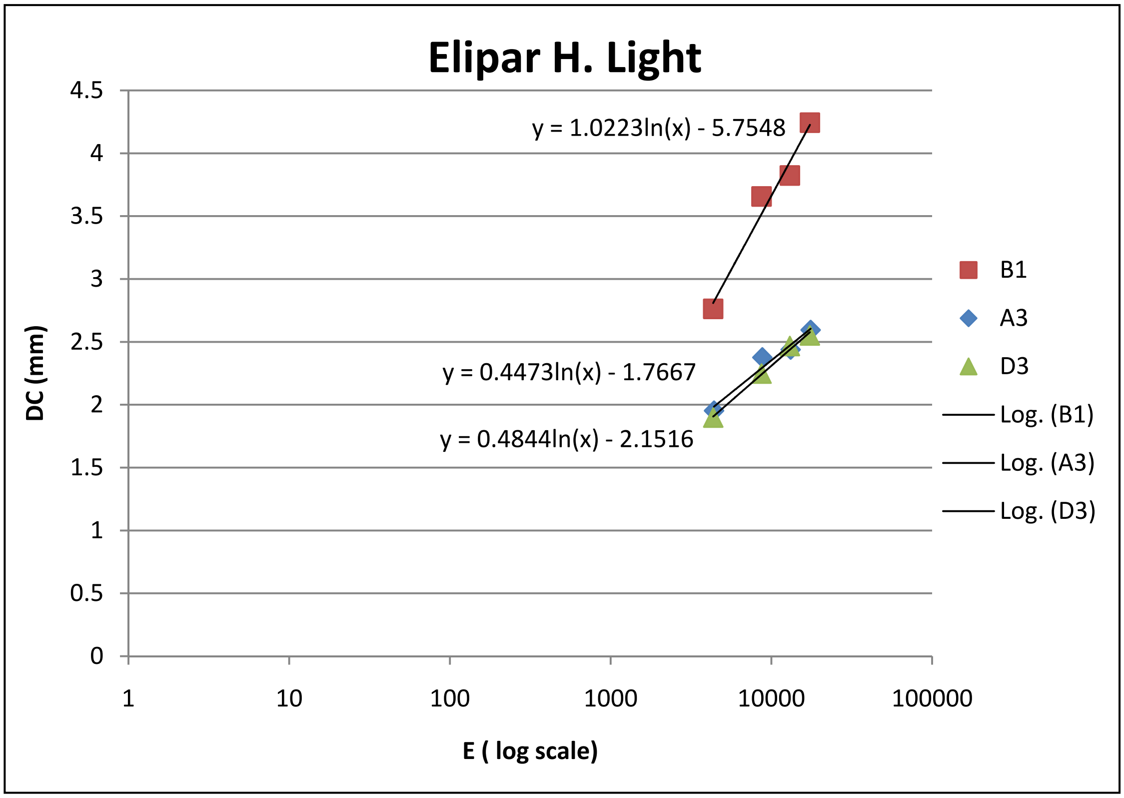

Figure 10. Regression lines of the different resin shades cured under Elipar High Light: Output energy in logarithmic scale vs. depth of cure in mm's.

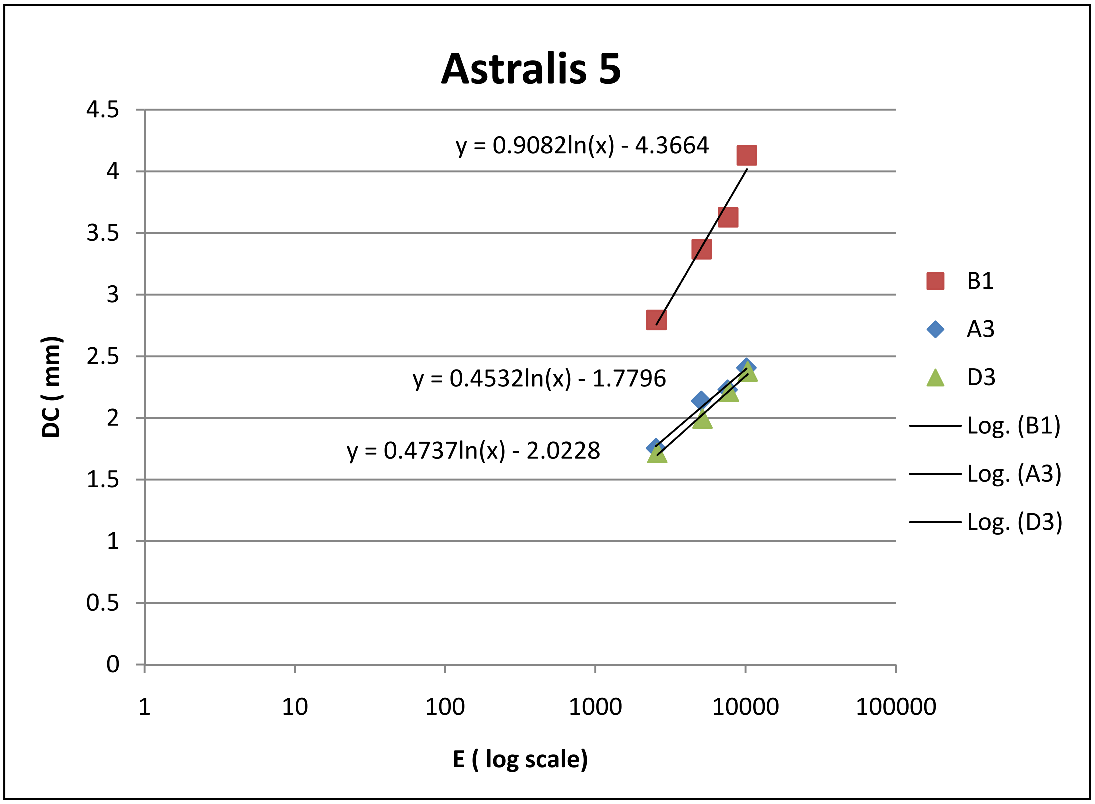

Figure 11: Regression lines of the different resin shades cured under Astralis 5 light: Output energy in logarithmic scale vs. depth of cure in mm's.

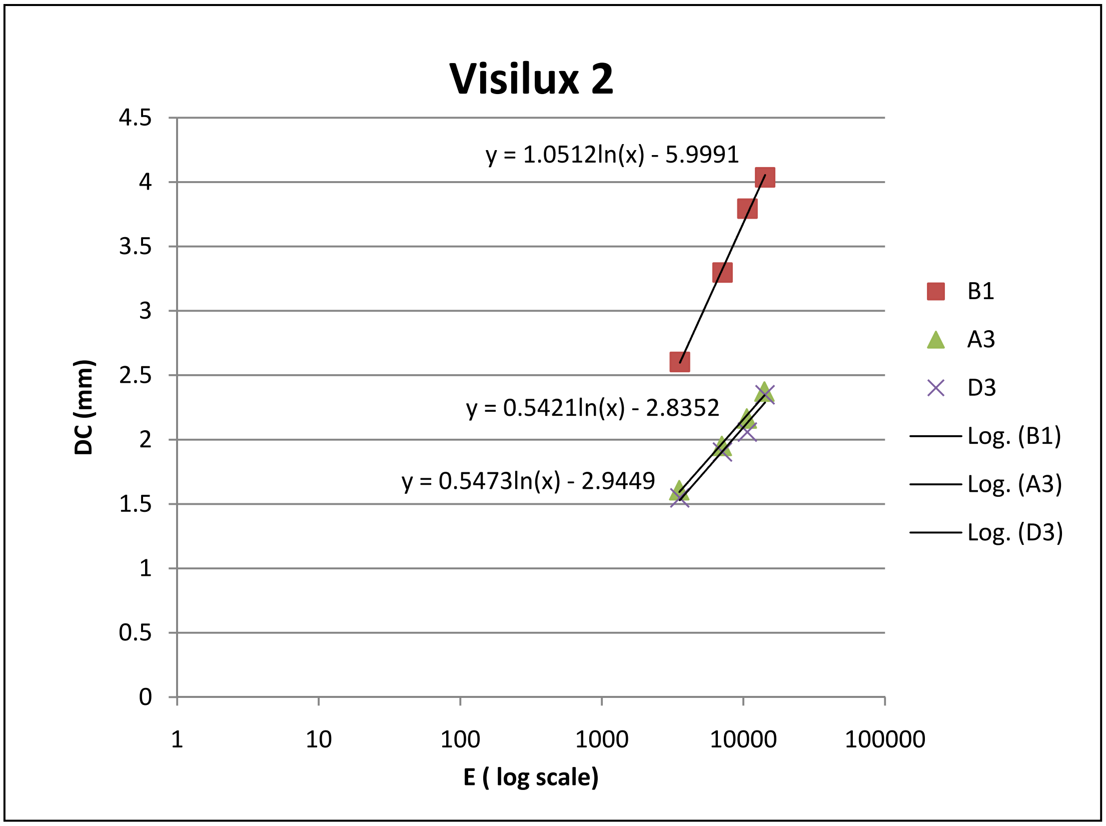

Figure 12. Regression lines of the different resin shades cured under Visilux 2 light: Output energy in logarithmic scale vs. depth of cure in mm's.

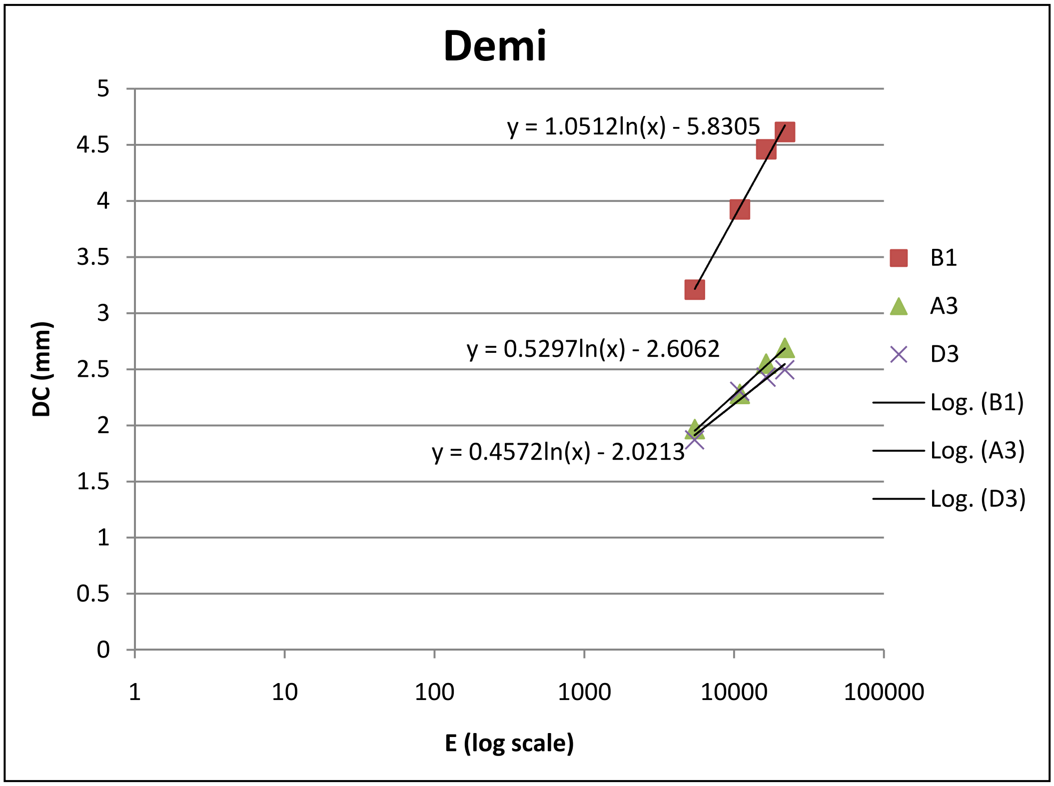

Figure 13. Regression lines of the different resin shades cured under Demi light: Output energy in logarithmic scale vs. depth of cure in mm's.

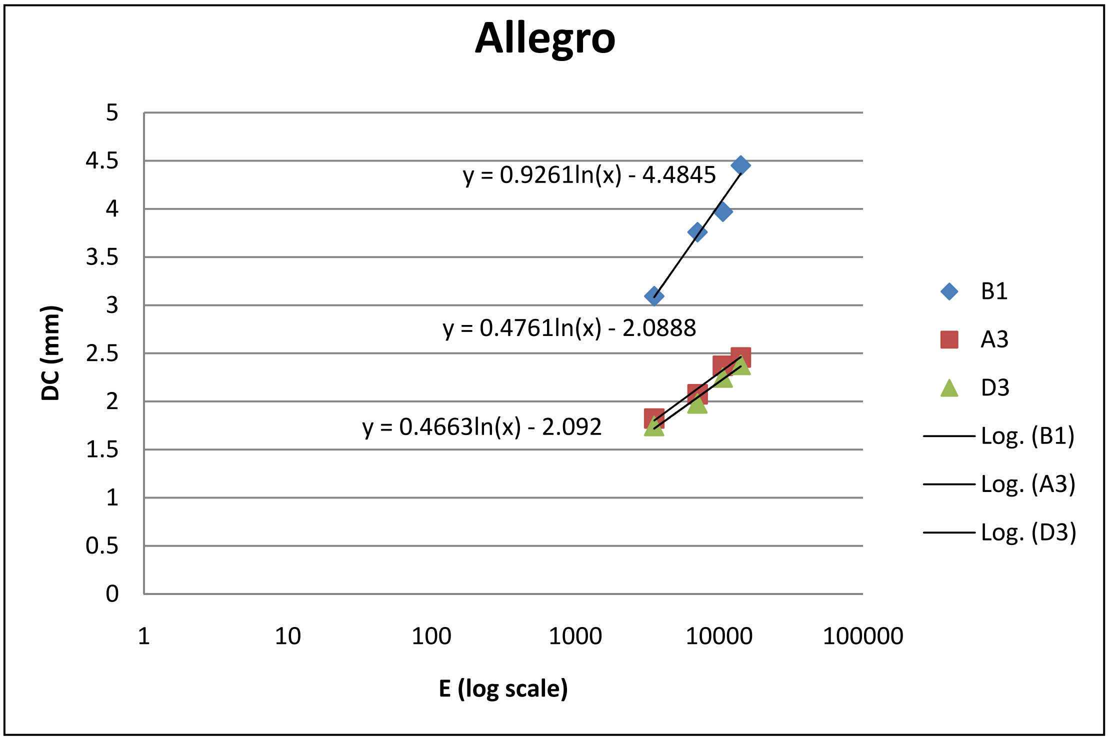

Figure 14. Regression lines of the different resin shades cured under Allegro light: Output energy in logarithmic scale vs. depth of cure in mm's.

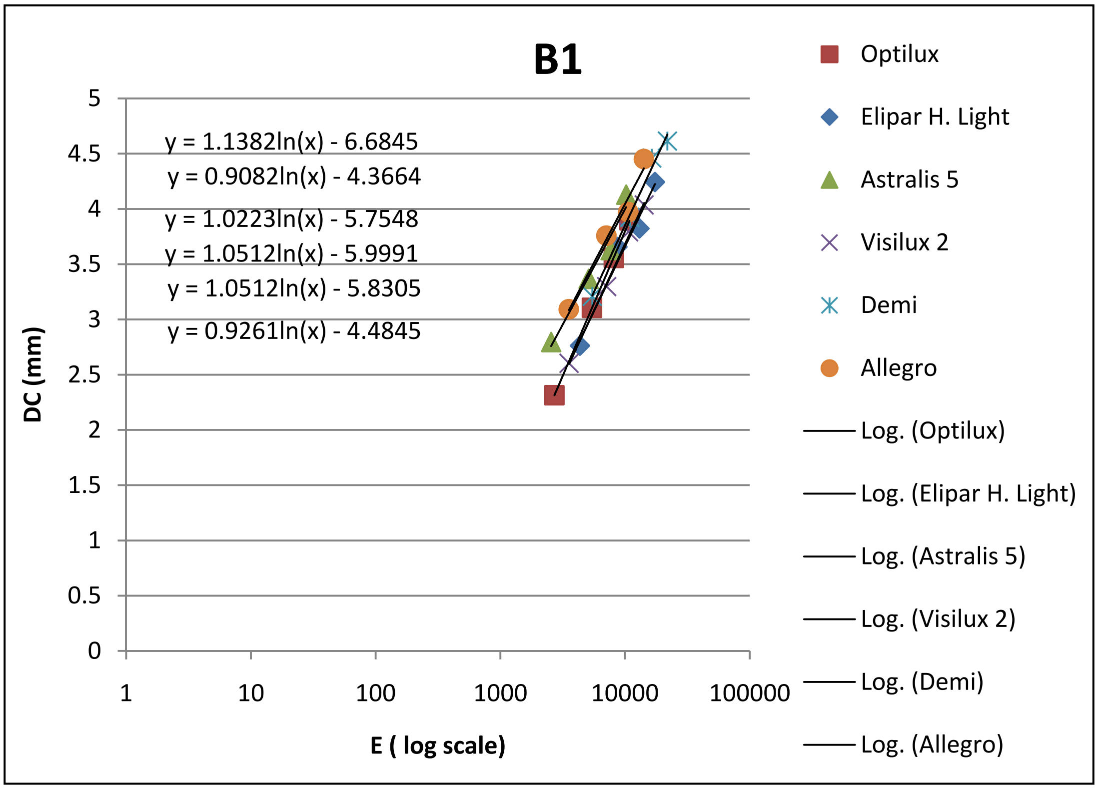

Figure 15. Regression lines of the different lights curing B1 shade samples: Output energy in logarithmic scale vs. depth of cure in mm's .

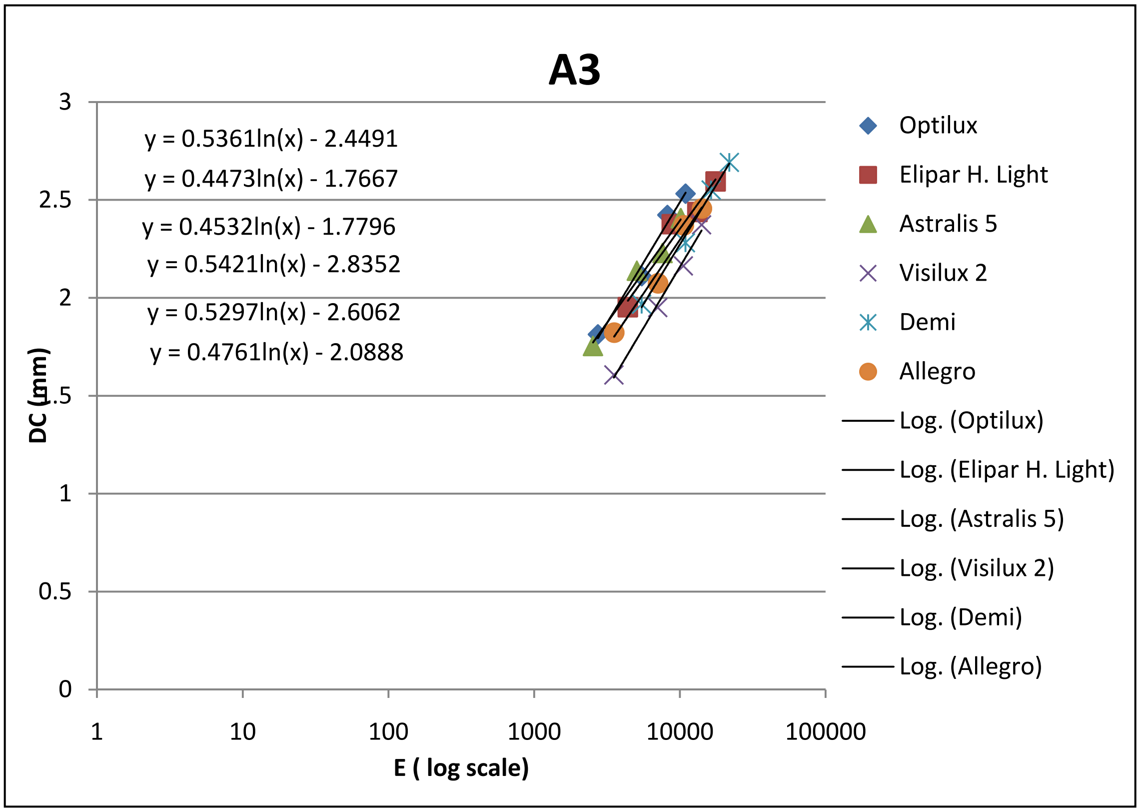

Figure 16. Regression lines of the different lights curing A3 shade samples: Output energy in logarithmic scale vs. depth of cure in mm's.

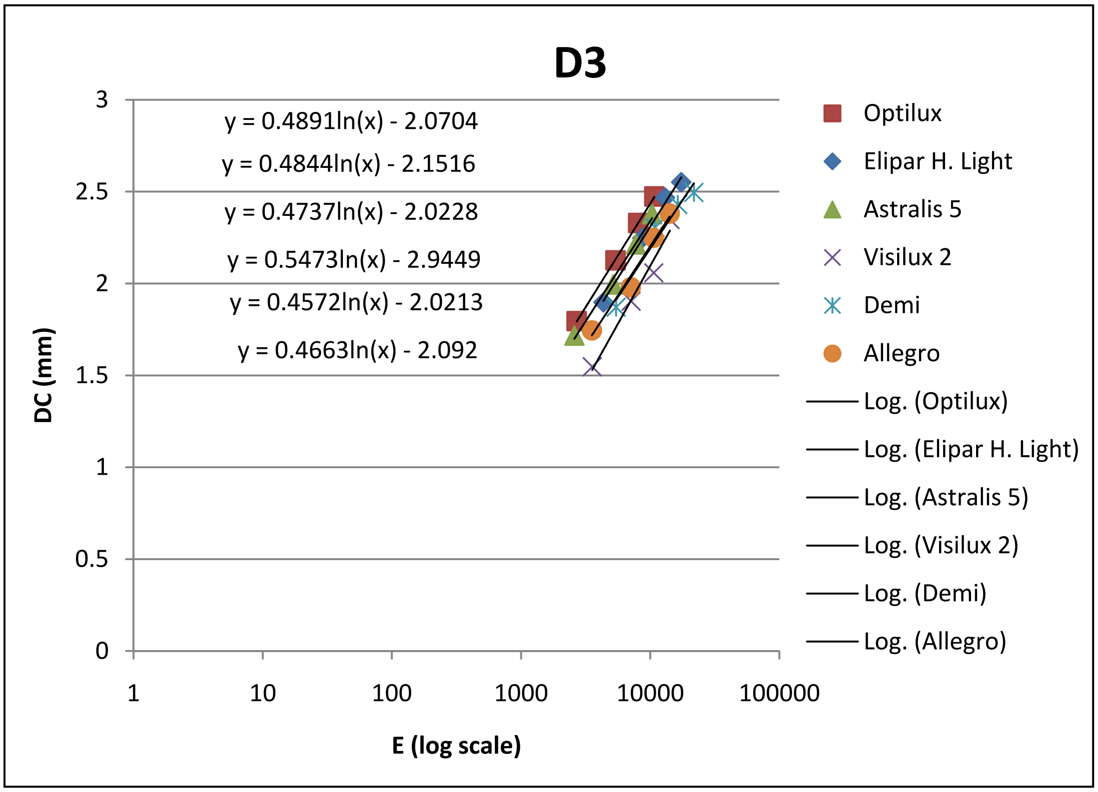

Figure 17. Regression lines of the different lights curing D3 shade samples: Output energy in logarithmic scale vs. depth of cure in mm's.

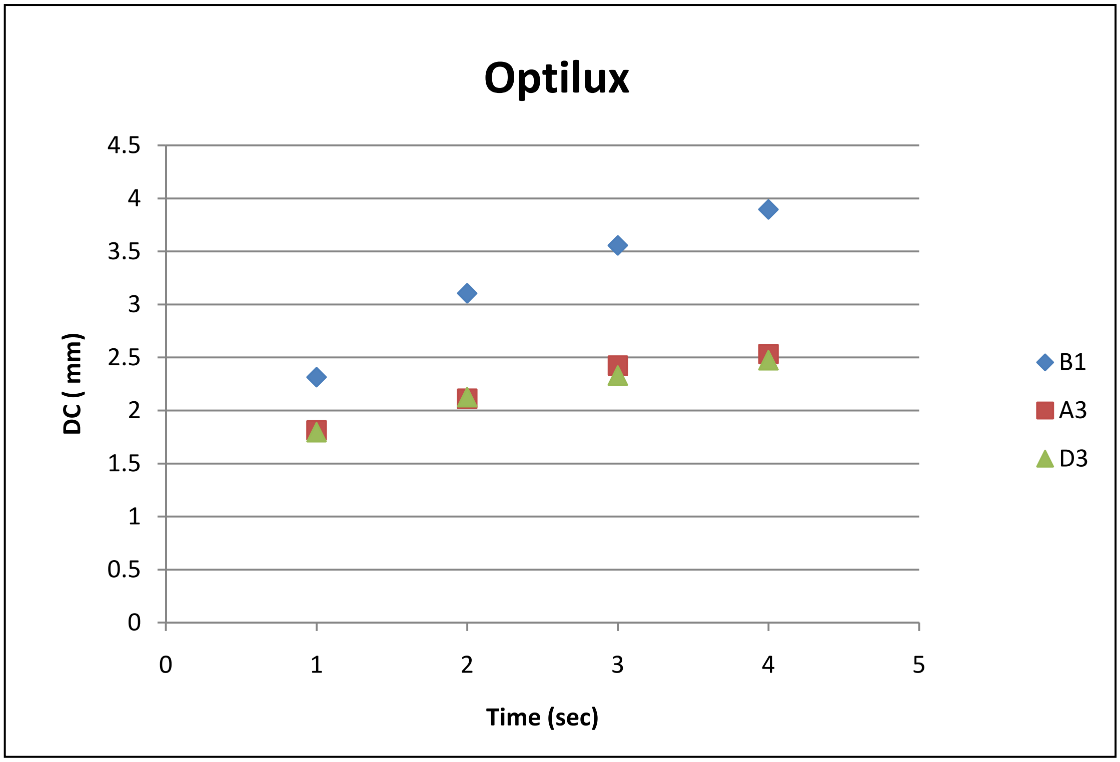

Figure 18. Regression lines of the different resin shades cured under Optilux light: Exposure duration in seconds vs. depth of cure in mm's.

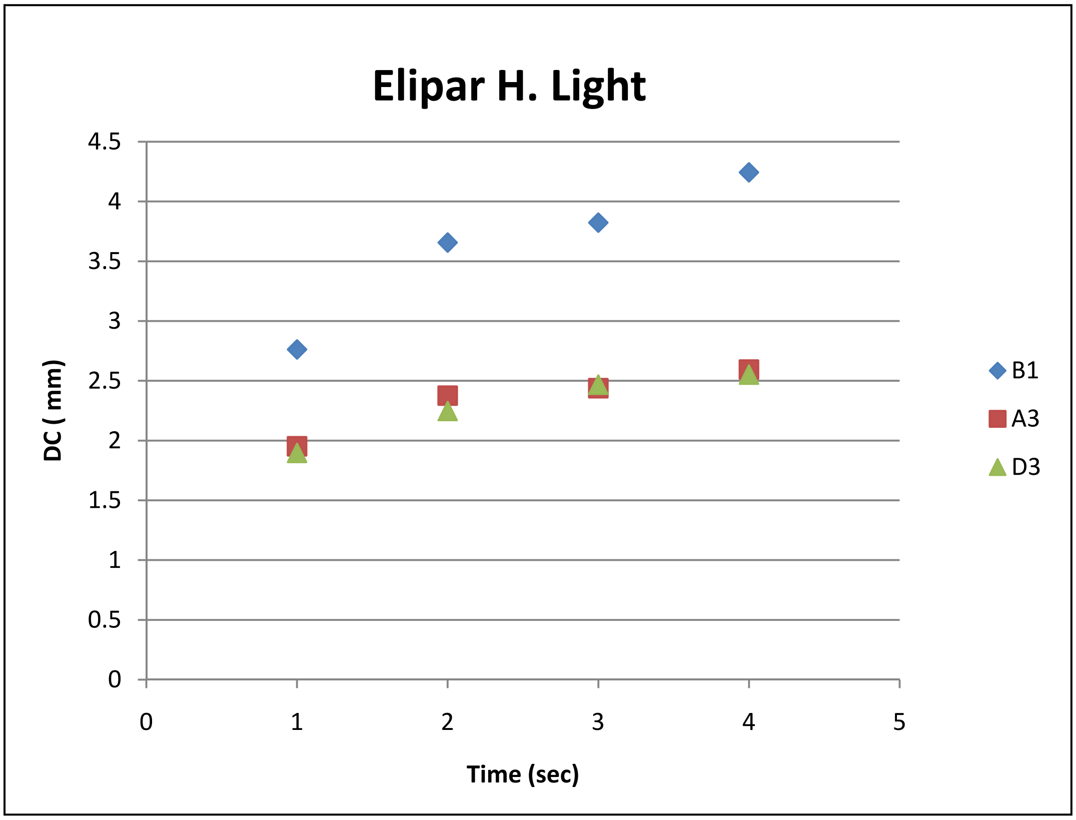

Figure 19. Regression lines of the different resin shades cured under Elipar H. light: Exposure duration in seconds vs. depth of cure in mm's.

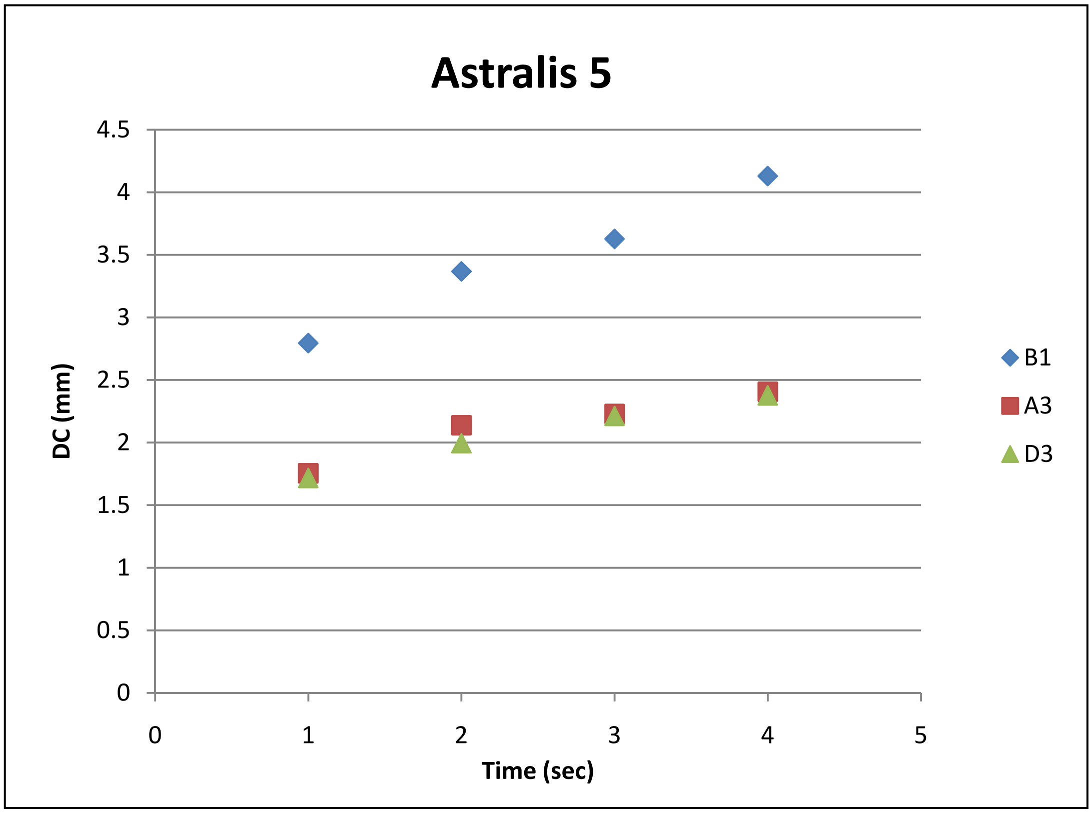

Figure 20. Regression lines of the different resin shades cured under Astralis 5 light: Exposure duration in seconds vs. depth of cure in mm's.

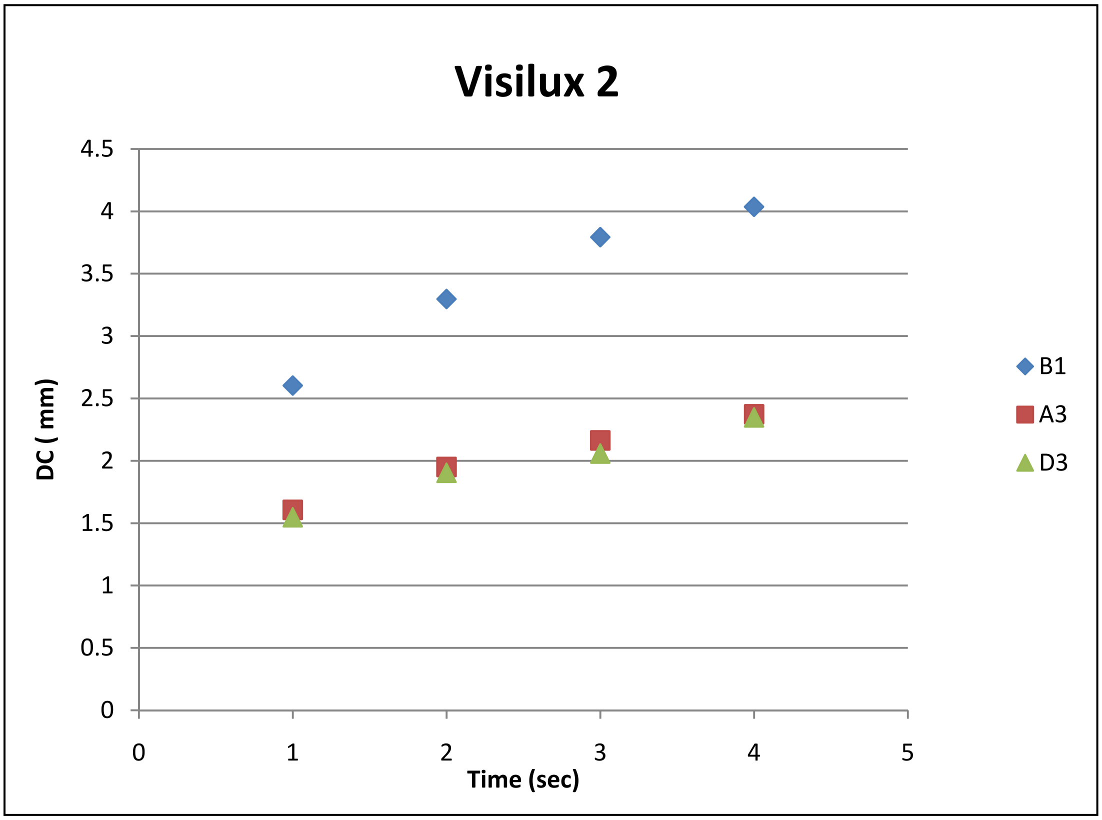

Figure 21. Regression lines of the different resin shades cured under Visilux 2 light: Exposure duration in seconds vs. depth of cure in mm's.

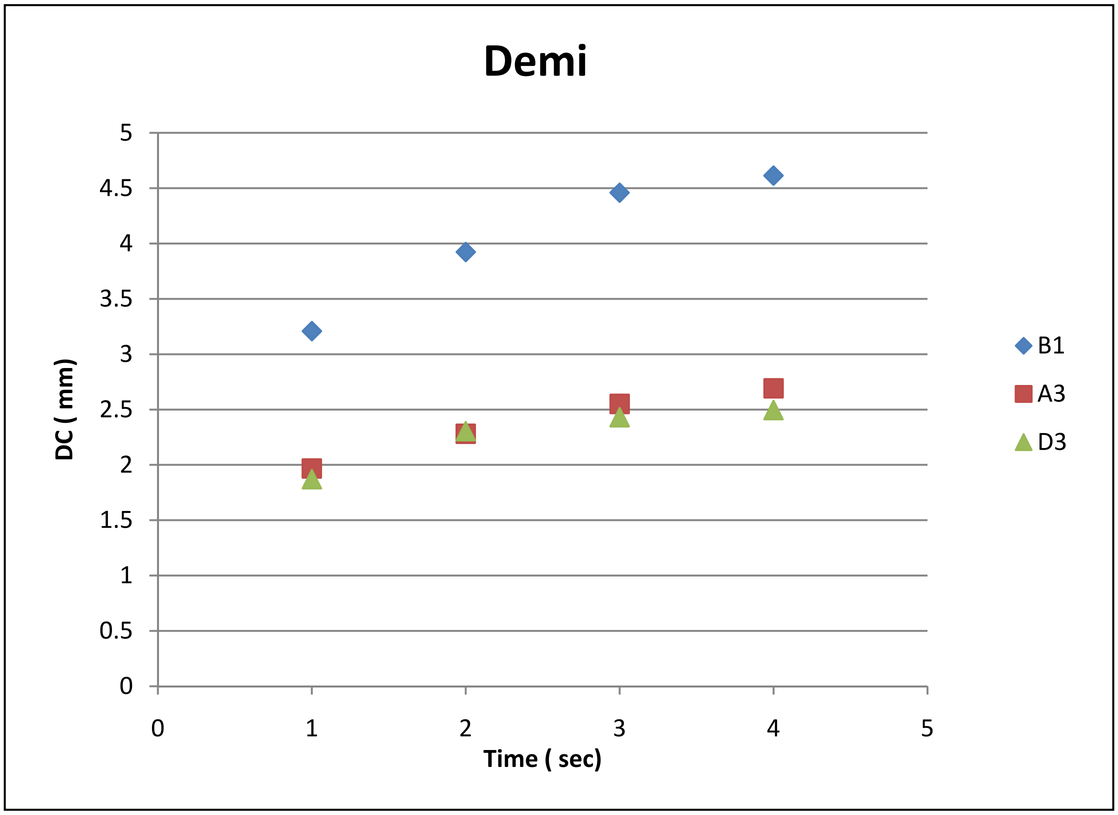

Figure 22. Regression lines of the different resin shades cured under Demi light: Exposure duration in seconds vs. depth of cure in mm’s.

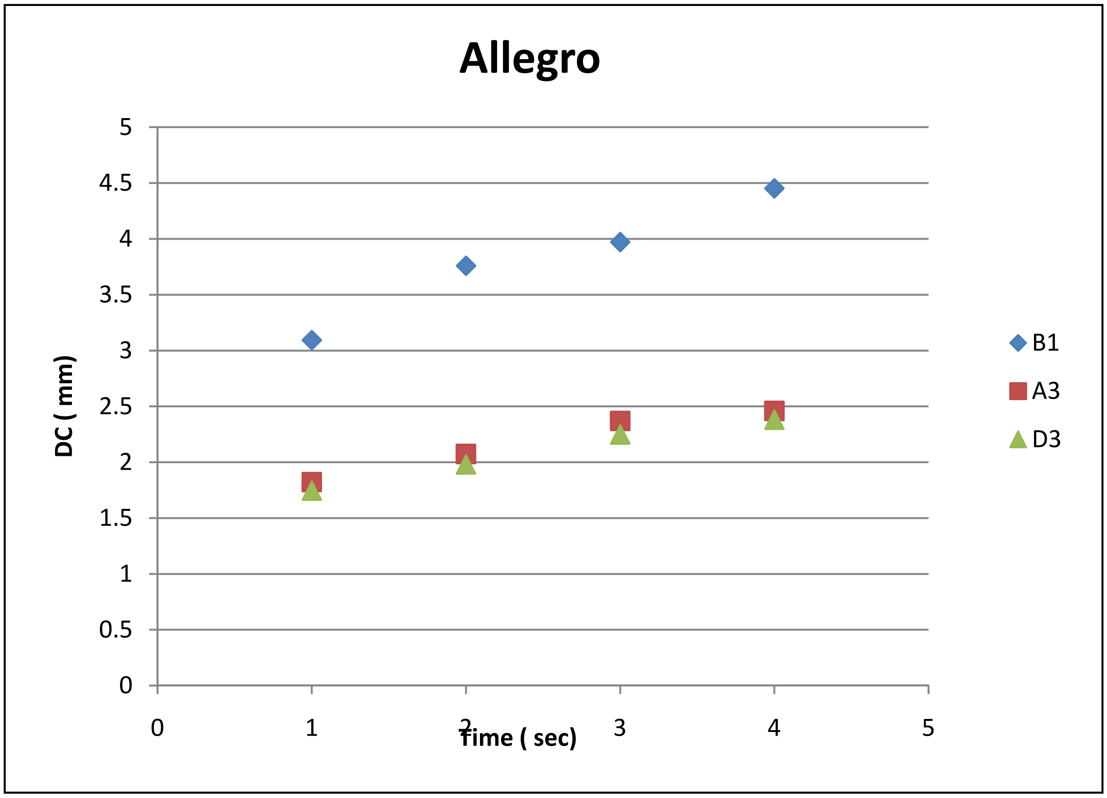

Figure 23. Regression lines of the different resin shades cured under Allegro light: Exposure duration in seconds vs. depth of cure in mm's.

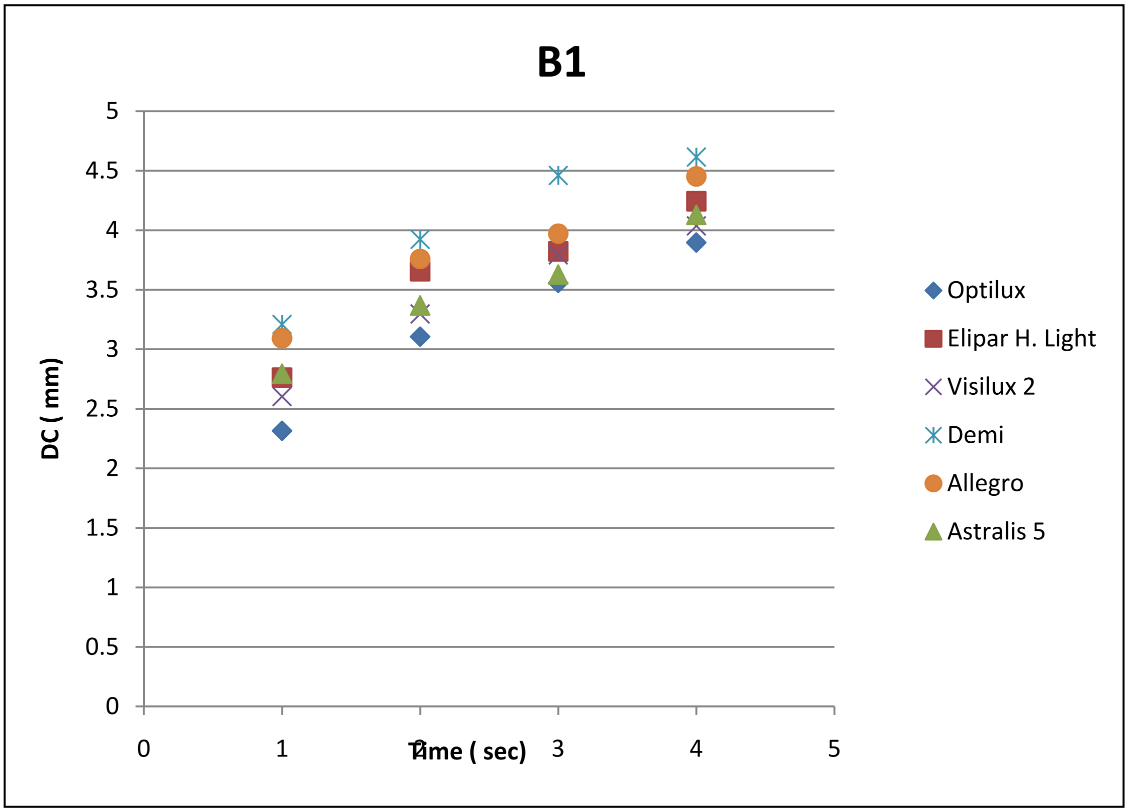

Figure 24. Regression lines of the different lights curing B1 shade samples: Exposure duration in seconds vs. depth of cure in mm's.

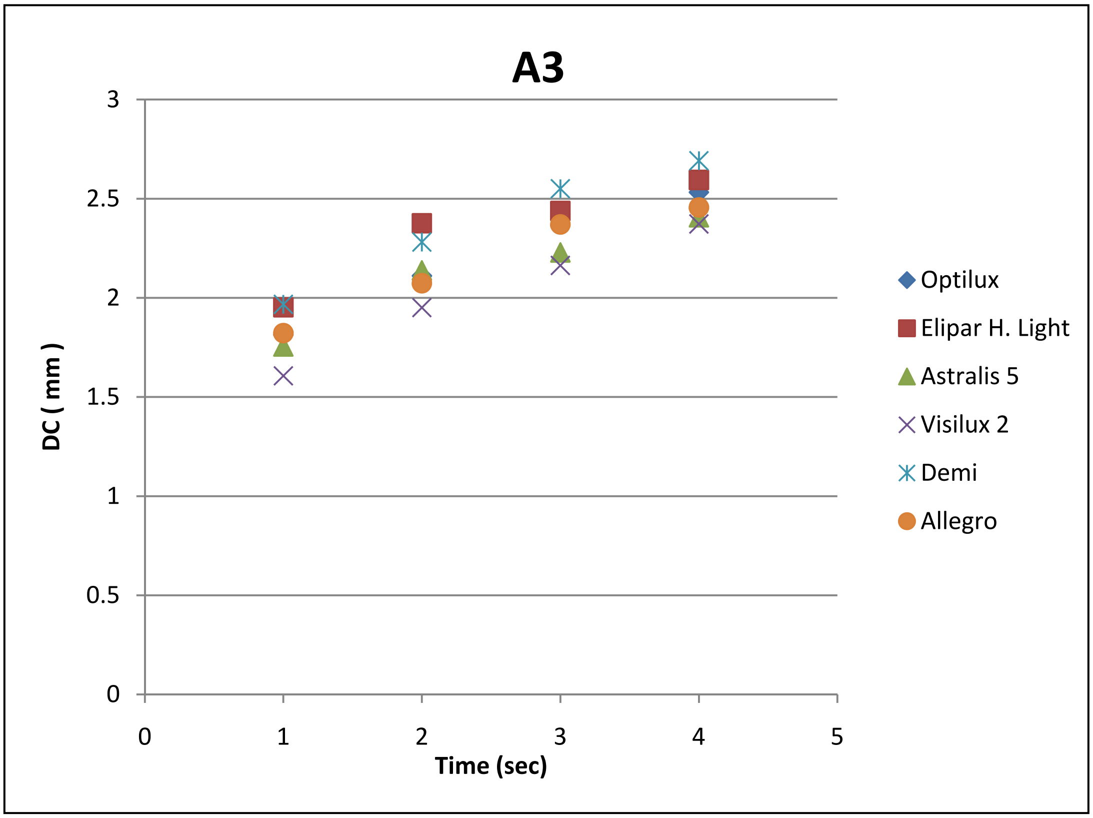

Figure 25. Regression lines of the different lights curing A3 shade samples: Exposure duration in seconds vs. depth of cure in mm’s.

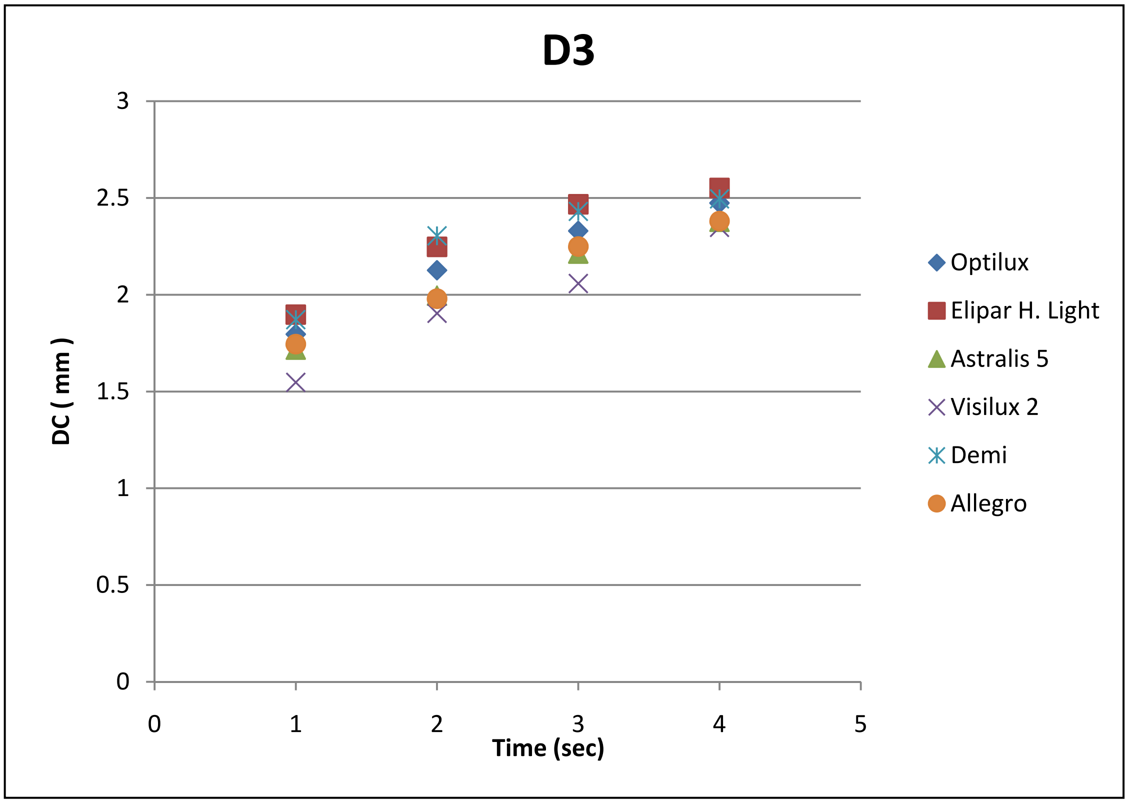

Figure 26. Regression lines of the different lights curing D3 shade samples: Exposure duration in seconds vs. depth of cure in mm's.

DISCUSSION

Several mathematical models were mentioned in the literature to predict the depth of cure in VLDC's. The advantage of the model used in this study is that both parameters D_p and E_c can be explained in terms of energy which provides a physical meaning that helps to understand this particular model. For example, a high D_p value refers to a greater penetration of the photons through the material bulk and a deeper depth of cure, while a high E_c value means that the critical amount of energy needed to form the gel layer within the resin composite is high [2].

The ISO scraping technique is chosen in this study to measure the depth of cure of the resin specimens because it requires minimum instrumentation and provides similar or more conservative values than those determined by other methods like IR spectroscopy or hardness tests.[22] The ISO defines depth of cure as 50 percent of the length of the composite specimen after the uncured material is removed with a plastic spatula.[10] Although a number of researchers attempted to use the total remaining length after scarping away the uncured material, many studies confirmed a significant reduction in the hardness of the composite specimen from the top surface to the bottom.[11, 23, 24] If the total length is used, under-polymerization would be the result and the clinical performance would be compromised.[22] Also, the 50 percent roughly corresponds to 80-percent polymerization of the polymer which provides sufficient strength to the material, thus, the ISO[10] selected 50 percent of the remaining length as a determination of the depth of the cure in light cured resin composites.

During the experiment, it was found that most of the B1 shade samples would cure deeper than 6mm which is the depth of the 1st original Teflon™ mold used in the study. So, to avoid any false results it was decided to remake all the B1 samples using a new Teflon™ mold 4 X 12mm.

For the light type effect on the parameters of the mathematical model used in this study, the D_p and E_c values were significant between some of LED and halogen lights, but that significance was not consistent enough between all the groups to confirm that LED or halogen lights are significantly different from each other regarding their effects on the parameters of the mathematical model in this study. For example, when comparing between the halogen and LED curing lights, it was found that the D_p value was significant ($P < 0.05$) between Allegro vs. Optilux for only B1 shade, Astralis 5 vs. Demi, Astralis 5 vs. Visilux 2 for shade A3 and B1, Demi vs. Elipar High light, and Elipar High Light vs. Visilux 2 only for A3 shade (Table IV). Several studies have concluded that the effect of light type by itself, whether LED or halogen, is not significant on the depth of cure of VLDC's.[18-20] However, In these studies, the interaction of light type with other factors like exposure duration or shade presented significant affects on the depth of cure of VLDC's.

For the effect of the light output intensity, the results of the study indicate that all the curing lights used meat the ISO minimum requirement (1.5mm) for the depth of cure in resin composites. Although the effect on D_p and E_c values was significant between a number of the curing lights, the results were not consistent enough to conclude that the source output intensity by itself can significantly affect the parameters of the mathematical model used in this study. For example, in the A3 shade-light combination group (Table V), Demi and Elipar High Light were significantly different in both D_p and E_c, while none of the parameters were significantly different between Demi and Optilux; even though the ouptput intensity difference between Optilux and Demi is much more than between Elipar High Light and Demi. Other similar situations occurred within the same and other shade-light combination groups. A possible explanation might be the wavelength differences between the curing lights. In a study by Nomoto,[13] it was confirmed that in the 450-490 nm wavelength range, the polymerization and depth of cure of VLDC's would primarily be affected by the exposure energy rather than the light wavelength; however, in other ranges, the wavelength might have a more dominant effect over the exposure energy regarding the polymerization and depth of cure of VLDC's. In our study, it is not possible to make any conclusions regarding the effect of wavelength since this factor was not measured through the experiment.

According to Rueggeberg,[14] It was reported that the effect of source output intensity on the depth of cure of VLDC's is more critical at the deeper portions of the cured material. At the superficial surface, where no overlaying composite interferes with light transmission, a curing light with relatively low intensity can cure the resin surface to the same degree as a high intensity curing light. However, as light transmits through the thickness of resin matrix, the light intensity decreases which leads to a decrease in the polymerization and curing efficiency.[25] To compensate for this decrease in the curing efficiency, the exposure duration must be usually increased to ensure adequate polymerization of the resin material. For this reason, many studies have recommended the use of dental curing lights with a minimum output intensity of 400mW/cm^2 to avoid any waste of clinical chair time and ensure sufficient polymerization within the bulk of of VLDC .

For the shade effect, the results of this study confirm that the shade has a more dominant effect on the parameters D_p and E_c compared to light type or light output intensity. Overall, most of B1 shade-light combinations had significantly ($P<0.05$) higher D_p and E_c values than the A3 and D3 shade-light combination (Tables IV and VIII) and no significant differences were found between the A3 and D3 groups (Table VIII). According to Katsileri,[2] the concentration of the photo-Initiator Camphorquinone in B1 shade resins is usually the least to achieve the lighter and whiter shade compared to A3 and D3 shades. Because of that, in the lighter shades, light penetrates deeper through the material bulk and that gives a higher D_p value. Also, due to the less photo-initiator concentration in the lighter shade, light absorption would be less. This means that the amount of energy necessary to form the gel layer within the resin is higher, which leads to higher E_c values. This comes in agreement with a number of studies which confirmed greater depth of cure for the lighter shades of VLDC's.[22, 26-28] Other studies suggest that the depth of cure of VLDC's might be more dependent on translucency than the shade factor.[29] However, the B1 resin in this study is more translucent than the A3 or D3 resins and that supports the greater depth of cure for the B1 shade samples. In another study, it was concluded that the shade effect is one of the influential factors on the depth of cure at the superficial surface of the resin, while at greater depths, other factors like exposure energy and duration are more determintial.[30]

This study again shows the two different interests in the study of curing depth of VLDC's. From the material science perspective, the total curing energy (intensity X time) versus cure depth provides a clearer comparison between lights and shows the effect of curing energy on cure depth. The use of curing energy instead of curing time in the x-axis of the chart (Figures 9 through 17) provides a standardized basis for comparison since it is the light total energy that determines the cure depth. This type of standardized comparison should be used when comparing the effect of curing light on depth of cure in VLDC's. When comparing the effect of different curing lights and with the energy standardized, the only difference will be the wavelength spectrum of the light. If we are only using curing time to compare the cure depth, since all lights have different output intensity, the energy at the same time interval will be different from light to light and thus not providing a "fair" comparison between lights.

However, from the clinicians' perspective, it is the curing time that provides an intuitive understanding on the performance of the light they have in their hands. Also, most of the commercial dental curing lights come with a pre -set output intensity, thus leaving the clinicians with one factor under their control which is the exposure duration. Comparison charts using the curing time as the x-axis (Figures 18 through 26) provide a clearer picture to the clinician as how the depth of cure will increase with increasing the curing time for a given light. This type of comparison is thus still important to clinicians, though the correlation between the polymerization physics and the depth of cure is lost.

Nonetheless, it is important to explore the full range of the cure depth at all energy levels (or curing times) instead of just measuring the depth of cure at one time point. As we can see from the chart, the curing curve of how the depth of cure increases with energy (or time) is different from light to light. One light may produce a lower depth of cure at a short curing time compared to a second light. The same light can produce a higher depth of cure at a longer curing time compared to a different light. Just comparing it at one time point (one energy level) will not allow one to see the full picture of the curing behavior of the light.

SUMMARY AND CONCLUSIONS

Depth of cure is an important parameter in evaluating the clinical usefulness of visible light dental composites VLDC's. Several factors affect the depth of cure in VLDC's such as material composition, shade, exposure duration, light type, light output intensity, and peak wavelength.

The purpose of this study was to further investigate the effect of using six different light source types with different light output intensities on the parameters of a mathematical model that predicts the DOC in VLDC's. In this equation: $D = D_p \ In(E_0/E_c)$, D is the depth of cure in millimeters, E is the curing energy in J/cm^2, E_c is the critical curing energy for the composite to reach a gel layer, and D_p is a characteristic coefficient.

Three LED and three halogen dental curing units with different light output intensities were used to cure three shades (B1, A3, D3) of a hybrid resin composite. The exposure duration was at the intervals of 10, 20, 30, and 40 seconds for each sample setting. ISO scraping technique was performed to measure the depth of cure of each sample. Regression analysis was used to assess the fit of the proposed mathematical model $D = D_p \ In(E_0/E_c)$ to the experimental data obtained in this study.

Within the limited scope of this experimental study, the following conclusions were drawn:

1) Several factors play combined influential effects on the kinetics of polymerization and depth of cure in VLDC's.

2) The shade has a more dominant effect on both parameters D_p and E_c than the curing light type or source output intensity.
3) As we cure lighter shades “B1”, the effect of using different lights with different output intensities on the two parameters D_p and E_c will be greater and more significant than for darker shades “A3 or D3”.
4) Clinicians should recognize that using curing lights with increased output intensities doesn’t absolutely increase the DOC of VLDC’s especially with the darker shades.

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ABSTRACT

THE EFFECT OF USING VARIABLE CURING LIGHT TYPES AND INTENSITIES ON THE PARAMETERS OF A MATHEMATICAL MODEL THAT PREDICTS THE DEPTH OF CURE OF LIGHT-ACTIVATED DENTAL COMPOSITES

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The purpose of this study is to further investigate the effect of using six different light source types with different light output intensities on the parameters of a mathematical model that predicts the DOC in VLDC's. In this equation: $D = D_p \mathrm{In}(E_0/E_c)$, D is the depth of cure in millimeters, E is the curing energy in J/cm^2, E_c is the critical curing energy for the composite to reach a gel layer, and D_p is a characteristic coefficient.

Three LED and three halogen dental curing units with different light output intensities were used to cure three shades (B1, A3, D3) of a hybrid resin composite. The exposure duration was at the intervals of 10, 20, 30, and 40 seconds for each sample setting. ISO scraping technique was performed to measure the depth of cure of each sample. Regression analysis was used to assess the fit of the proposed mathematical model $D = D_p \mathrm{In}(E_0/E_c)$ to the experimental data obtained in this study.

For all the shade-light combinations; A3, B1, and D3 had significantly different regression lines ($P < 0.05$) with significantly higher D_p and E_c for B1 than A3 and D3. The only exceptions were for the E_c values between B1 and D3 in Allegro, Astralis 5, and Visilux 2 groups; and the E_c between A3 and B1 in Allegro group. The D_p and E_c parameters didn't show significant differences between A3 and D3 shades in all the groups. Also, most of the significant differences for D_p values occurred in the B1 shade-light combinations; however, none of the D3 shade-light combinations showed significant differences for D_p.

Several factors play combined influential effects on the kinetics of polymerization and depth of cure in VLDC's. The shade has a more dominant effect on both parameters D_p and E_c than the curing light type or source output intensity. As we cure lighter shades "B1," the effect of using different lights with different output intensities on the two parameters D_p and E_c will be greater and more significant than for darker shades "A3 or D3." The clinical significance drawn from this study is that clinicians should recognize that using curing lights w/ increased output intensities doesn't absolutely increase the DOC of VLDC's especially with the darker shades.

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