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Laboratory Research

The Effect of Light Curing Source on the Residual Yellowing of Resin Composites

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Clinical Relevance

The selection of light curing unit (quartz-tungsten-halogen or blue light-emitting diode), composite classification and shade have an influence on the amount of residual yellow after photocuring and, in some combinations, the color difference may be visually detectable.

SUMMARY

Purpose. This study evaluated the amount of residual yellow in cured resin composites when polymerizing with either a quartz-tungsten-halogen (QTH) or blue light-emitting diode (LED). Material and Methods: Twelve shades (bleaching to conventional shades) of microfill, hybrid and microhybrid resin composite specimens (n=10) were polymerized with both light types. All the materials contained only camphorquinone as the photoinitiator. After exposure, the specimens were stored in the dark for 24 hours. Then, the specimen color parameters were recorded (L^*, a^*, b^* and C^*_{ab}) and color differences (ΔE^*_{ab}) were determined by examining for changes among the test combinations. Group comparisons were examined using ANOVA and the Tukey-Kramer post-hoc test, and pairwise comparisons were made using Student's *t*-tests at a pre-set alpha of 0.05. Results: When a significant difference in residual yellow was noted, the QTH light produced a greater yellow tinge than most comparisons using the LED. The potential for producing more residual yellowing could not be anticipated with respect to composite filler classification or shade, as this effect may be more dependent on individual product composition. The extent to which residual yellowing differences were noted between light curing unit types fell within levels considered detectable by the human eye ($\Delta E>2.0$).

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Conclusion: The selection of light curing unit to polymerize resin-based restorative materials can have a significant influence on the amount of residual yellow present, with the QTH light tending to leave more yellow than an LED unit.

INTRODUCTION

Because the human eye is more sensitive to changes in lighter shades, the ability to anticipate the final color characteristics of a resin composite used for restoring bleached teeth becomes even more important.[1-2] The most common photoinitiator used in light-cured restorative materials is camphorquinone (CQ).[3-5] This compound is relatively inefficient in forming radicals and requires an accelerator (typically an aliphatic amine, such as DMAEMA) so that exposure durations, which are practical to the clinician and patient, can occur.[6] CQ-based systems worked well for color shades that do not involve the high values required when restoring bleached teeth.[7] CQ is bright, canary yellow in color and, even though it is added in only small amounts, it significantly contributes to the presence of a yellowish tinge in the final restoration.[8] In order to eliminate this color influence, manufacturers have used a variety of "alternative initiators," which are UV initiators having a small absorbance in the short visible wavelength range (shorter than 430 nm). These initiators are colorless; therefore, they do not impart a yellow tinge in the final restoration.[9-11]

Still, CQ remains the most commonly used initiator, despite its subtle influence on color in the final restoration. A characteristic of this molecule, like many other photoinitiators, is that it has the capability to "photobleach" after reacting.[12] In this process, the chemical structure of CQ is changed to that of a pinocol,[13] which is white but still has significant absorption in the UV range. Thus, as CQ is used, it has the potential to have less of an influence on the color of the final restoration.[14-16]

The visible absorption profile of CQ is quite broad, ranging from 390 to 510 nm, peaking near 465 nm.[13,17] This profile provides an indication of the different electron configurations of bonds in CQ at any given time, as each bond is associated with a different frequency of energy. Because of its non-linear absorption, CQ would be most reactive to visible light photons delivered in a wavelength range of its highest absorption value: between 425 and 490 nm.[18-20]

The most common photocuring unit in dentistry has been the quartz-tungsten-halogen light (QTH). This source provides a non-linear output that covers the entire visible spectral range needed by CQ, and the spectral emission profile correlates well with the spectral absorbance profile of CQ. Thus, this source delivers photons that could be absorbed by every electron state that exists in CQ within visible light.[21] However, the new light-emitting diode (LED) units (those emitting only a "blue" output near 450 to 470 nm) supply only a narrow range of photons, but the quantity of the photons delivered exceeds that from a QTH source within the same range (Figure 1). This spectral range occurs where the most common electron configurations of CQ exist, and these lights are thus quite effective in activating this material.[20] Contemporary LEDs dwarf the irradiance of QTH light units within this wavelength range, thus making the LED light a far more effective light curing unit.[18]

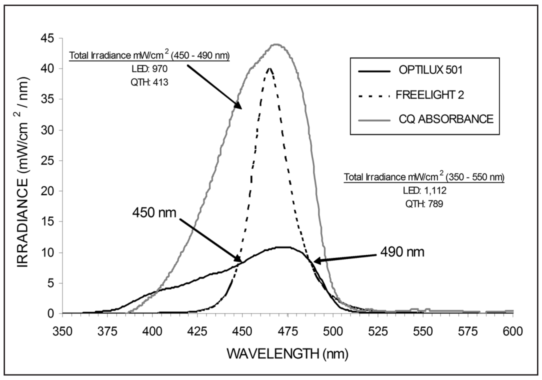

Figure 1: *Spectral overlay of light curing units used.*

The blue LED unit provides only a small range of wavelengths that are absorbable by CQ, and, thus, this unit has the potential to leave behind unreacted photoinitiator that did not receive visible irradiation However, the QTH light is broad banded and covers the entire visible frequency range of CQ absorbance. Thus, a residual pool of unactivated CQ molecules may exist, which has not been exposed when using a blue LED curing light. If the LED light leaves more unreacted CQ than the QTH source, it is reasonable to expect that the same CQ-based resin composite exposed to these two different light sources may be different in color after exposure, with the LED light yielding slightly more yellow than that resulting from the QTH source. Knowledge of this potential effect may have significant implications on the success of color matching in esthetic dentistry.

Thus, this study evaluated the effect of curing light spectral bandwidth (wide, QTH; narrow LED), type of composite classification (microfill, microhybrid, hybrid) and composite shade (light to bleaching) on the amount of residual yellowing in cured composite specimens, all of which were CQ-based. The research hypothesis tested was that composites photo-cured using the LED light would demonstrate more yellow (greater b*) than would the same composite cured with a QTH unit.

METHODS AND MATERIALS

A variety of photo-curable resin composites, representing three different classifications based on filler con-

Table 1: *Composites Used*

Brand Name	Classification	Shade	Lot #	Manufacturer	Filler (wt %)*
Filtek A110	Microfill	B0.5	20030613	3M/ESPE, St Paul, MN, USA	79
		B1	20030404		
		A1	20030613		
		A2	20030605		
Prodigy	Hybrid	XL	307269	Kerr Corp, Orange, CA, USA	56
		B1	304776		
		A1	303047		
		A2	305576		
EsthetX	Microhybrid	W	301292	LD Caulk, Milford, DE, USA	77
		XL	302012		
		B1	302012		
		A2	305164		

**per manufacturer's information*

tent: microfill, hybrid and microhybrid (Table 1), were selected. Within each product, a range of shades was used, including CQ-based bleaching shades and conventional Vita shades. Two shades (A2 and B1) were selected as common to all products. The light curing units used were a conventional quartz-tungsten-halogen (QTH) light (Optilux 501, Demetron Research Corporation, Danbury, CT, USA) and a second-generation blue light emitting diode (LED) (Elipar FreeLight2, 3M/ESPE, St Paul, MN, USA). Spectral irradiance profiles were made for each light using a laboratory-grade spectral radiometer (DAS2100, Labsphere, Sutton, NH, USA) and a three-inch integrating sphere. Power density measurements of both curing lights were made periodically throughout the testing, and the battery-operated LED unit was charged between each exposure. The spectral absorbance of camphorquinone (lot #12,489-3 Aldrich Chemical, Milwaukee, WI, USA) was obtained in a UV-VIS spectrometer (CHEM2000- UV-VIS, Ocean Optics, Dunedin, FL, USA) using methanol as the solvent.

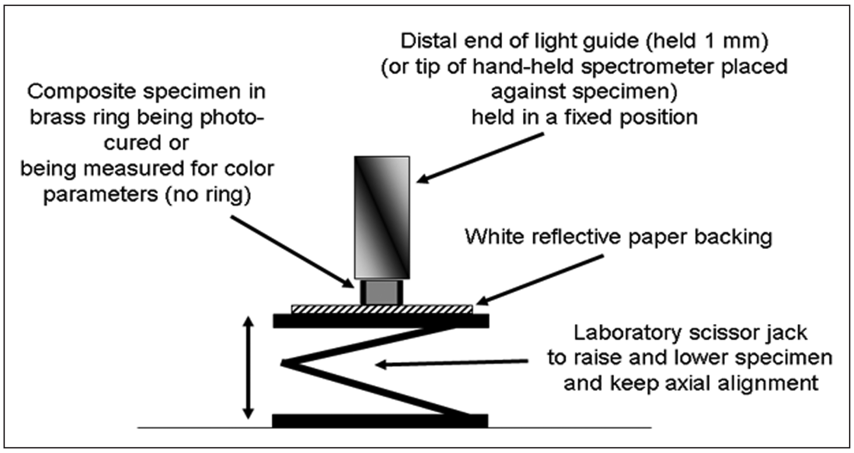

Figure 2: *Schematic diagram of specimen light-curing and color measurement setup.*

Cured Specimen Fabrication

A drop of optical immersion oil (Type B, Cargille Lab, Inc, Cedar Grove, NJ, USA) was placed on a white, wax-coated paper cement-mixing pad (#31299 Kerr, Orange, CA, USA), providing a consistent, reflective background. The oil served to displace any air interface and act as an optical conduit. A microscope glass plate (25x75x1 mm, item # 12-550C, Fisher Scientific, Norcross, GA, USA) was laid on the pad top, followed by a sheet of Mylar (Type D, DuPont Company, Wilmington, DE, USA). A brass ring (ID 6 mm, height 2 mm) was placed on the Mylar and uncured composite paste was inserted into the open end of the ring. After slightly overfilling, another Mylar sheet was placed on top of the ring, and a glass plate was used to flatten the material and force the composite to adapt to the mold dimensions and express excess material. The specimen and lower reflecting surface were placed on the horizontal plate of a 4” x 4“ lab jack (Fisherbrand lot #14-673-50) and raised vertically until the top Mylar surface was 1.0 mm from the distal end of the light curing guide (held rigidly in place). The test setup is schematically represented in Figure 2. The composite specimens (n=10) were exposed to light curing (20 seconds LED, 40 seconds QTH). Brass rings surrounding the cured composite specimens were removed, and the specimens were then placed in a dark drawer at room temperature for at least 24 hours prior to color reading. One operator fabricated all the specimens.

Color Measurement

To help join the specimen to the white backing optically, a drop of the same immersion oil was placed on the same white background material that was used to make the specimens; the aged specimens were then placed against the background (non-exposed side towards the oil). The sheet and specimen were then placed on the same jack stand used for specimen fabrication and raised vertically to meet the probe end of an intraoral spectrophotometer (Vita, EasyShade, Vident, Brea, CA, USA) until the probe end made contact with the center of the exposed polymerized specimen top surface (Figure 2). The color parameters L*, a*, b* and C^*_{ab} were recorded for each specimen. Color differences (ΔE^*_{ab}) were calculated for each shade of product between those obtained using the QTH and LED lights.[21] One operator obtained all the color readings.

Specimen Monomer Conversion

Following curing and subsequent color measurement, the infrared spectra of the top and bottom (2 mm deep) surfaces of each of five specimens randomly selected from the experimental groups were obtained. The flat surface (top and bottom) of each specimen was pressed against the surface of a horizontal diamond in an attenuated total reflectance attachment (Golden Gate, SPECAC, Woodstock, GA, USA) placed within the optical bench of a Fourier transform infrared spectrometer (FTS-40, Digilab/ Bio-Rad, Cambridge, MA, USA). A total of 16 spectra were obtained and averaged to derive a single specimen profile at a resolution of 2 cm^{-1}. Spectra of the uncured composite were obtained by pressing a small amount of paste directly onto the diamond surface. Monomer conversion of each specimen was determined using methods previously outlined in the literature.[22-24] Basically, these methods utilize changes in the ratio of aliphatic C=C (1636 cm^{-1}) to aromatic C-C (1608 cm^{-1}) in the cured and uncured states. The percent monomeric aliphatic C=C bonds converted into C-C bonds was thus determined (monomer conversion).

Statistics

Within the b* values for each composite type, a two-way ANOVA was performed to observe the effect of both shade and curing light type on this parameter. Each color parameter value (L*, a*, b*, C^*_{ab}) measured within a shade for a specific composite type was compared between use of the QTH and LED lights using an unpaired, two-tailed Students *t*-test. All statistical testing was performed at a pre-set alpha of 0.05. Monomer conversion values were compared between similar surfaces of a composite type exposed to either the LED or the QTH light using a two-tailed, unpaired Student's *t*-test at the same alpha level previously stated.

Table 2: *Percent Monomer Conversion Values (Mean [sd]) of All Composites and Light Curing Units Tested*

			Composite Surface	
Composite	**Shade**	**Light**	**Top**	**2 mm**
EsthetX (Microhybrid)	A2	LED	66.6 (0.5)	64.6 (0.5)
		QTH	69.0 (0.8)	65.1 (0.6)
		p-value	0.01201	0.12233
	B1	LED	65.8 (2.1)	65.0 (0.7)
		QTH	67.4 (1.2)	63.6 (2.1)
		p-value	0.28459	0.21438
	W	LED	64.5 (1.1)	63.6 (1.2)
		QTH	65.6 (1.7)	66.7 (3.8)
		p-value	0.22409	0.39621
	XL	LED	67.5 (1.3)	65.7 (0.8)
		QTH	66.6 (0.9)	65.1 (0.6)
		p-value	0.06626	0.08500
Filtek A110 (Microfill)	A1E	LED	63.0 (1.0)	63.2 (0.5)
		QTH	65.3 (0.7)	63.8 (0.8)
		p-value	0.09036	0.46457
	A2E	LED	62.8 (0.6)	59.5 (1.7)
		QTH	63.5 (0.5)	60.1 (0.7)
		p-value	0.09892	0.41929
	B0.5	LED	62.4 (1.3)	60.0 (0.8)
		QTH	64.7 (0.7)	60.1 (0.5)
		p-value	0.02135	0.69667
	B1	LED	61.7 (0.5)	59.4 (0.8)
		QTH	63.1 (0.5)	59.0 (2.1)
		p-value	0.03425	0.66240
Prodigy (Hybrid)	A1	LED	70.2 (0.4)	68.3 (0.8)
		QTH	71.7 (0.8)	69.3 (1.0)
		p-value	0.03665	0.41456
	A2	LED	67.7 (0.2)	65.8 (2.2)
		QTH	73.8 (0.5)	71.1 (0.5)
		p-value	0.00059	0.03529
	B1	LED	70.7 (1.2)	69.3 (1.6)
		QTH	70.4 (1.6)	70.6 (1.2)
		p-value	0.86839	0.33062
	XL	LED	70.4 (0.7)	67.4 (1.8)
		QTH	71.7 (0.7)	69.3 (0.8)
		p-value	0.46659	0.12423

n=5 specimens per experimental group

RESULTS

Table 2 presents monomer conversion values obtained when comparing values for similar surfaces between light curing unit types for a given composite material and shade. Of the possible 24 comparisons made, only six were found to be significantly different, with five of those occurring for the top surface comparisons. Among the five comparisons, the top surface conversion was found to be greater when the QTH light was used, but absolute percentage values differed by approximately 2%. The exception noted occurred with Prodigy A2, which showed the QTH surface having a value 6.1% higher than when the LED light was used. That material was the only one that demonstrated a significant difference in conversion values between light unit types at the bottom surface. Again, the QTH light yielded a higher conversion value (5.3% greater) than that seen using the LED unit.

Table 3 displays differences in all color parameters obtained between QTH and LED lights. Significant differences in each color parameter were noted between use of the different curing sources. The hybrid product produced the greatest number of significant differences within color parameters with respect to light use, followed by the microhybrid, with the microfilled product producing the least (comparison of shaded areas within a composite type in Table 2). The color parameter most affected by curing light type was a*. Within that parameter, all shades of the hybrid and microhybrid showed a significant effect of light type use, while only B1 of the microfilled material was affected. There was a trend towards the QTH light producing a more red-tinted product than the LED, but some comparisons indicated that the LED light made specimens less red. An equal proportion of significant differences was noted when comparing parameter differences of L*, b* and C^*_{ab}, but they were distributed differently among products and shades. The L* of the microhybrid composite was most affected, with the bleaching shades (W and XL) producing a lighter (higher L* value) than the shade than the LED, but with the A2 shade being darker. Within this parameter, the B1 and A1 shades of the microfill were lighter when cured with the LED, while the XL and A1 shades of the hybrid were lighter using the QTH light.

The two-way ANOVAs for b* values indicated that shade significantly affected this parameter for each of the three composite types (*p*=0.0001). The type of light used had a significant impact on all b* values (*p*=0.0001), except for the microhybrid material (*p*=0.8019). A significant interaction (*p*=0.0001) between shade and light source type existed for all composite types, with the exception of the hybrid material (*p*=0.2428). All shades of the hybrid composite type demonstrated a significant effect of curing light type, with the QTH light indicating a higher b* value (more yellow) compared to using the LED. Of all the comparisons of b* shown to be significantly affected by light curing type, most (6 out of 7) showed that use of the QTH light produced more yellow (higher b* value) than when the LED light was used. Only the W shade of the microhybrid indicated more of a yellow product with the LED.

With respect to C^*_{ab} (chroma), the same products and shades that were significantly affected by light curing type in the b* parameter were also shown to be affected for this parameter. Among these significant findings, the same trends for effect of curing light type were also noted.

The greatest difference in overall color (ΔE^*_{ab}) with respect to use of light curing unit was seen for the B1

Table 3: *Color Parameters Measured (mean [sd])*

			L*		a*		b*		Cab* (chroma)		
			dark (-)	light (+)	red (+)	green (-)	yellow (+)	blue(-)	low (-)	high (+)	ΔE*ab
Brand	Classification	Shade	QTH	LED	QTH	LED	QTH	LED	QTH	LED	QTH-LED
A110	Microfill	B0.5	84.8 (0.9)	85.3 (0.6)	6.0 (0.2)	6.1 (0.3)	50.6 (0.6)	50.6 (0.7)	50.9 (0.6)	51.0 (0.7)	0.5
		B1	81.2 (2.2)	83.9 (0.4)	6.8 (0.6)	5.8 (0.3)	47.2 (1.4)	44.2 (1.2)	47.7 (1.4)	44.6 (1.2)	4.1
		A1	82.8 (0.5)	83.8 (0.7)	0.2 (0.3)	0.4 (0.4)	31.4 (0.6)	31.2 (1.1)	31.4 (0.6)	31.2 (1.1)	1.0
		A2	79.9 (0.7)	79.6 (0.4)	1.3 (0.3)	1.4 (0.2)	39.7 (1.4)	38.9 (0.5)	39.7 (1.4)	39.0 (0.5)	0.8
Prodigy	Hybrid	XL	93.9 (0.8)	92.6 (1.5)	-1.2 (0.1)	- 0.9 (0.2)	11.7 (0.3)	9.3 (0.5)	11.8 (0.3)	9.3 (0.5)	2.7
		B1	89.4 (1.0)	90.0 (0.9)	1.6 (0.2)	2.1 (0.3)	26.3 (0.7)	24.7 (0.9)	26.4 (0.7)	24.8 (1.0)	1.8
		A1	88.7 (0.7)	87.5 (1.0)	2.4 (0.2)	1.9 (0.3)	25.2 (0.7)	22.8 (1.1)	25.3 (0.7)	22.9 (1.1)	2.7
		A2	83.4 (0.5)	83.1 (0.6)	5.2 (0.1)	4.8 (0.3)	33.5 (0.4)	31.1 (0.8)	33.9 (0.4)	31.5 (0.8)	2.5
EsthetX	Microhybrid	W	93.0 (0.5)	91.8 (-1.1)	-2.1 (0.3)	-1.5 (0.3)	20.5 (0.6)	21.5 (0.4)	20.6 (0.6)	21.6 (0.4)	1.7
		XL	89.4 (0.5)	88.3 (1.5)	-1.6 (0.3)	-1.9 (0.4)	15.1 (0.7)	15.8 (1.3)	15.2 (0.6)	16.0 (1.2)	1.4
		B1	87.8 (0.6)	87.1 (0.9)	-1.3 (0.3)	-1.5 (0.2)	22.4 (0.7)	20.7 (0.5)	22.5 (0.7)	20.7 (0.4)	1.9
		A2	82.8 (2.1)	85.1 (0.9)	4.5 (0.4)	4.4 (0.5)	32.8 (0.8)	32.6 (1.1)	33.1 (0.8)	32.9 (1.2)	2.3

n=10 specimens/experimental group

Within a color parameter and shade, shadowed cells indicate values were significantly different between curing light types (p<0.05) shade of the microfill: ΔE^*_{ab}= 4.1. The balance of values within the composite classification was much lower, spanning from 0.5 to 1.0. The microhybrid composite indicated the next higher range of ΔE^*_{ab} values, spanning from 1.4 to 2.3. As a group, the composite classification showing the highest ΔE^*_{ab} values for all shades was the hybrid product, ranging from 1.8 to 2.7.

Figure 1 shows the differences in irradiance profiles of the curing lights used and the spectral absorbance of camphorquinone. The absorbance of CQ is seen to peak near 468 nm and fall off rapidly on either side, more rapidly at longer wavelengths. The total irradiance of the lights used differed greatly, with QTH providing 789 mW/cm^2 and LED generating 1,112 mW/cm^2 as measured between 350 and 550 nm. However, within the region where CQ absorbs very highly (450–490 nm), irradiance delivered from the LED light (970 mW/cm^2) was more than twice that from the QTH source (413 mW/cm^2). Thus, for equivalent exposure durations, the LED light would also supply more than twice the energy density (irradiance x exposure) within this spectral range than would the QTH source.

DISCUSSION

The research hypothesis, that use of the LED light would result in cured composite materials that were more yellow (higher b* value) than those polymerized using the QTH light, was proven false. Among those comparisons with b* that demonstrated a significant affect of light curing unit use, six of the seven observed showed that the QTH light produced a higher b* value (were more yellow) than those cured using the LED light. The reason for this finding may be related to the fact that, once CQ absorbs a photon of light and further reacts, its entire visible absorption profile is altered and not just a small wave length range. It was thought that irradiation of CQ with the LED light would have utilized CQ molecules only within a narrow bandwidth, leaving behind residual, unreacted CQ having absorption frequencies not included in the LED emission still available. However, the data indicate that, because of the greater power density (and thus energy density) of the LED light, more total CQ molecules may have been consumed, resulting in higher amounts of photo bleaching and less residual, unreacted product left to provide the yellow tint in the cured product.[18-19] This assumption seems logical, in that the proportion of power delivered to the composites where CQ had its highest absorbance values (450–490 nm) was provided by the LED light, and not from the QTH (Figure 1). The spectral irradiance data obtained from the lights used in the study support the fact that far more power was delivered between these wavelength ranges from the LED source than was obtained using the QTH light.

It is interesting to note that the effect of light curing unit on b* value could not be predicted with respect to composite classification or shade. Because of its higher total resin content, it may be expected that the microfilled material would have demonstrated greater color difference when exposed to the two curing lights. However, this composite classification demonstrated the least change of all composite types but also displayed the highest overall color change of all the materials tested: ΔE^*_{ab} of 4.1 for the B1 shade. The b* color differences for the other B1 composite types showed less than half of this ΔE^*_{ab} value: the hybrid was 1.8 and the microhybrid was 1.9. The reason for the high color change of this specific brand shade is not known. When comparing a lower value shade (A2) among the three composite types, the microfill and microhybrid products were not affected by choice of curing light, but by the hybrid product. Within the very high value (bleaching) shades, the W shade of the microhybrid showed increased yellowing when the LED light was used, but the XL shade was not affected and neither was the high value microfill shade (B0.5). These findings indicate that shade cannot be used as a predictor of the degree of residual yellow color anticipated, but composite classification may be. However, composite classification may be a predictor. All shades of the hybrid product indicated a significant yellowing with use of the QTH light but only with one each of the microhybrid and microfill. Ruling out shade as an overall factor, these results indicate that differences in resin and photoactivator formulation may be a causative factor. However, because the composition of these products is not known, an exact correlation between these parameters and the potential for leaving a residual yellow color cannot be made.

The color parameter showing the greatest effect of choice of light curing unit was a*. All shades of the hybrid and microhybrid were affected, but only one shade of the microfill. Within this parameter though, there was no clear distinction as to the effect of one light unit over the other.

The value (L*) of composites was also affected by the selection of light type, but no overwhelming trends were observed among the composites and shades. Among the materials, similar shades (either A2 or B1) behaved differently. The color parameter of "value" can be affected by the extent of resin cure. As a material increases in cure, it undergoes changes in translucency, but these changes are not uniform among composite classifications.[16]

It is interesting to note that the exact same comparisons found to be significantly different, and the trend of those changes seen for b*, are reflected in the C^*_{ab} (a measure of chroma) result as well. The parameter C^*_{ab} is a calculation that includes both the results from a* and b* parameters.[21] Thus, these results indicate that, although many significant differences in a* were found, the overwhelming influence on the chroma resulted from differing b* values. Because the chroma changes reflected those of b*, it was found that, when significant differences in C^*_{ab} are correlated with respect to light type, the overwhelming trend is that the QTH unit produces a composite with higher chroma (more saturation).

Resin composites undergo color changes during visible light curing, and some of these changes may be perceived by humans due to a high ΔE.[14,16,19] Some authors consider a ΔE^*_{ab} value of ≤2.0 as the limit of clinically perceptible color differences,[1] while others consider a $\Delta E^*_{ab} \geq 3.7$ to be a poor match.[7] Other authors suggest a ΔE^*_{ab} value of 3.3 to be a reasonable number for determining perceptible color change of resin composites.[2] In this study, color comparisons were not made between uncured and cured products; instead, comparisons were made between cured composites arising from exposure to different light sources. The results of this study show that only one specific composite type and color (microfill, shade B1) produced a ΔE^*_{ab} value (4.1) that would definitely be perceptible to humans, as it exceeded all the limits suggested in all previous work. The hybrid product produced many ΔE^*_{ab} values between 2.5 and 2.7, while only one of the microhybrid shades (A2) produced a ΔE^*_{ab} greater than 2.0. These lower ΔE^*_{ab} numbers fall above the 2.0 threshold noted by some as being perceptible to humans and, thus, may have clinical relevance. If all the comparisons noted above are able to be detected visually, then 5 out of the 12 possible combinations of composite types and shades produced enough differences in color parameters when using a different type of LCU to be of clinical importance. Thus, the clinician may need to consider the effect of LCU type on the final color parameters of the restorative material when delivering an esthetic photo-activated resin composite.

Differences in composite conversion between light sources could have had an influence on color differences as well, because the translucency of the material is directly related to its extent of cure.[16] However, most comparisons did not indicate a significant difference in conversion between light types for the same composite and surface. There did not appear to be any correlation between the color differences observed and the conversion values measured when relating them to light type. For example, Prodigy A2 demonstrated the greatest difference in conversion between light unit types for both top and bottom surfaces. For that composite, light unit type was shown to affect the color parameters of a*, b* and C*. However, EsthetX B1, W, XL; Filtek A110 A1, A2 and Prodigy B1 and XL demonstrated significant differences in color with respect to light use, but none showed a difference in conversion value with respect to light source. It should be pointed out that, for most of the composites demonstrating a significant conversion difference (top surface) between lights, the difference in mean percentage values ranged over 2%. Such a small difference is not considered sufficiently significant to result in a color change so dramatic as to warrant a noticeable difference. These values also validate the exposure durations applied in this testing to provide for similar composite curing: LED 20 seconds and QTH 40 seconds. Therefore, the impact of monomer conversion differences that may have influenced observed color changes between light types has been negated.

In order to lessen the influence of the curing light source on final composite color, it is recommended that the clinician use a shade guide that has been made of the same composite polymerized with the same LCU unit that will be utilized clinically. In this manner, the best color match may be anticipated, taking into account the variances of the restorative material and the effects of differences in the spectral emissions among the LCU used.

It should be stressed that not all composites, nor all curing light types, were studied in this research. The specific correlations of the effects of color change with light unit type apply only to those materials tested. However, it is not unreasonable to assume that, because composites were selected to represent specific classifications, other commercial products may indicate similar types of susceptibility to color differences with respect to light unit used for photo curing.

CONCLUSIONS

Based on the limitations imposed by this study, the following conclusions may be made:

1. Selection of a light curing unit to photocure resin-based restorative materials can have a significant influence on the amount of residual yellow present in the cured restoration.
2. When a difference in yellow was noted, most often, the QTH light produced more of a yellow tint than did use of the LED unit for similar shades and classifications of composite.
3. The potential for producing a residual yellow tint cannot be accurately predicted with respect to composite filler classification or shade, as it appears to be more dependent on product composition.
4. The extent of residual yellowing in photocured composites, with respect to use of different light curing sources (QTH or LED), may be sufficiently high to be visually discernable.

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References

1. O'Brien WJ, Groh CL & Boenke KM (1990) A new, small-color-difference equation for dental shades *Journal of Dental Research* **69(11)** 1762-1764.
2. Ruyter IE, Nilner K & Moller B (1987) Color stability of dental composite resin materials for crown and bridge veneers *Dental Materials* **3(5)** 246-251.
3. Shintani H, Inoue T & Yamaki M (1985) Analysis of camphorquinone in visible light-cured composite resins *Dental Materials* **1(4)** 124-126.
4. Allen NS (1996) Photoinitiators for UV and visible curing of coatings: Mechanisms and properties *Journal of Photochemistry and Photobiology A: Chemistry* **100(1)** 101-107.
5. Rabek J, Fouassier J, Linden L, Nie J, Andrzejewska E, Jakubiak J, Paczkowski J, Wrzyszczynki A & Sionkowska A (1999) Camphorquinone/amine photoinitiating system for photocuring *Trends in Photochemistry & Photobiology* 51-61.
6. Nie J, Lindén LÅ, Rabek JF, Fouassier JP, Morlet-Savary F, Scigalski F, Wrzyszczynski A & Andrzejewska E (1998) A reappraisal of the photopolymerization kinetics of triethyleneglycol dimethacrylate initiated by camphorquinone-N,N-dimethyl-p-toluidine for dental purposes *Acta Polymer* **49(4)** 145-161.
7. Johnston WM & Kao EC (1989) Assessment of appearance match by visual observation and clinical colorimetry *Journal of Dental Research* **68(5)** 819-822.
8. Rueggeberg FA, Ergle JW & Lockwood PE (1997) Effect of photoinitiator level on properties of a light-cured and post-cure heated model resin system *Dental Materials* **13(6)** 360-364.
9. Neumann MG, Miranda WG Jr, Schmitt CC, Rueggeberg FA & Correa IC (2005) Molar extinction coefficients and the photon absorption efficiency of dental photoinitiators and light curing units *Journal of Dentistry* **33(6)** 525-532.
10. Sun GJ & Chae KH (2000) Properties of 2,3-butanedione and 1-phenyl-1,2-propanedione as new photosensitizers for visible light cured dental resin composites *Polymer* **41(16)** 6205-6212.
11. Park YJ, Chae KH & Rawls HR (1999) Development of a new photoinitiation system for dental light-cure composite resins *Dental Materials* **15(2)** 120-127.
12. Rutsch W, Dietliker K, Leppard D, Köhler M, Misev L, Kolczak U & Rist G (1996) Recent developments in photoinitiators *Progress in Organic Coatings* **27(1-4)** 227-239.
13. Cook WD (1992) Photopolymerization kinetics of dimethacrylates using the camphorquinone/amine initiator system *Polymer* **33(3)** 600-609.
14. Lee YK, Lim BS, Rhee SH, Yang HC & Powers JM (2004) Changes of optical properties of dental nano-filled resin composites after curing and thermocycling *Journal of Biomedical Materials Research Part-B Applied Biomaterials* **71(1)** 16-21.
15. Emami N & Söderholm KJM (2005) Influence of light-curing procedures and photo-initiator/co-initiator composition on the degree of conversion of light-curing resins *Journal of Materials Science: Materials in Medicine* **16(1)** 47-52.
16. Paravina RD, Ontiveros JC & Powers JM (2002) Curing-dependent changes in color and translucency parameter of composite bleach shades *Journal of Esthetic and Restorative Dentistry* **14(3)** 158-166.
17. Rueggeberg F (1999) Contemporary issues in photocuring *Compendium of Continuing Education in Dentistry* **25(Supplement)** S4-15.
18. Wiggins KM, Hartung M, Althoff O, Wastian C & Mitra SB (2004) Curing performance of a new-generation light-emitting diode dental curing unit *Journal of the American Dental Association* **135(10)** 1471-1479.
19. Usumez A, Ozturk N & Ozturk B (2005) Two-year color changes of light-cured composites: Influence of different light-curing units *Operative Dentistry* **30(5)** 655-660.
20. Chen Y, Ferracane J & Prahl S (2005) Quantum yield of conversion of the dental photoinitiator camphorquinone *SPIE Saratov Fall Meeting 2004: Optical Technologies in Biophysics & Medicine VI, 5771* 256-266.
21. Berns R (2000) Billmeyer and Saltzman's *Principles of Color Technology* John Wiley & Sons, Inc Canada 72.
22. Ruyter IE & Svendsen SA (1978) Remaining methacrylate groups in composite restorative materials *Acta Odontologica Scandanavia* **36(2)** 75-82.
23. Ferracane JL & Greener EH (1984) Fourier transform infrared analysis of degree of polymerization in unfilled resins—methods comparison *Journal of Dental Research* **63(8)** 1093-1095.

This PDF is the authors' corrected version and differs from the original print version by various corrections in the text.

Corrections

Changes/corrections have been made and are posted online for the following articles, which were published in *Operative Dentistry* **32-4** and **32-5**:

In Vitro Inhibition of Bacterial Growth Using Different Dental Adhesive Systems (R Walter, WR Duarte, PNR Pereira, HO Heymann, EJ Swift Jr & RR Arnold) **4** 388-392.

The Effect of Light Curing Source on the Residual Yellowing of Resin Composites (MG Brackett, WG Brackett, WD Browning & FA Rueggeberg) **5** 443-450.

In Vitro Comparison of Four Different Dental X-ray Films and Direct Digital Radiography for Proximal Caries Detection (MT Alkurt, I Peker, O Bala & B Altunkaynak) **5** 504-509.