Clin Oral Invest (2009) 13:29–35
DOI 10.1007/s00784-008-0221-9

ORIGINAL ARTICLE

Effect of tree types of light-curing units on 5-year colour changes of light-cured composite

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Received: 27 February 2008 / Accepted: 29 July 2008 / Published online: 4 September 2008

Abstract The purpose of this study was to determine colour changes in a composite cured with *tungsten-halogen*, light-emitting diode (LED) or a plasma arc after 5 years. Five specimens 10 mm in diameter and 2 mm in height were prepared using Hybrid (Clearfil AP-X) composite for each test group. The corresponding specimens were cured with a tungsten-halogen curing light, a LED unit or with a plasma arc. Specimens were stored in light-proof boxes for 5 years after the curing procedure to avoid further exposure to light and stored in 37°C in 100% humidity. Colorimetric values of the specimens immediately after curing and after 5 years were measured using colorimeter. The ΔE^*_{ab} values varied significantly depending on the curing unit used (p<0.001). Curing time did not affect the colour changes of the specimens (p=0.4). The results of this study suggest that composite materials undergo measurable changes due to the curing unit exposure.

Keywords Curing units · Composite · Colour change · Tungsten halogen · Light-emitting diode

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Introduction

Light-curing composite materials have been used as fillers in restorative dentistry for a number of years and are now an established alternative to dental amalgams [15, 49]; however, the appearance of composite restorations changes over time. External stain accumulation, marginal leakage, secondary caries and internal discolouration can make a restoration visually unacceptable. In addition to secondary caries, discolouration is one of the main reasons for the removal of composite fillings [34]. Water accumulation, changes in chemical compounds necessary for photopolymerization, photo-oxidation and other processes have been thought to be responsible for internal colour changes [11, 56, 59]. Until recently, light emitted from a tungsten-halogen light bulb has been used to cure composites. These types of curing units usually operate at light intensities between 400 and 800 mW/cm^2 and cure composite filling material within 40 s. Tungsten-halogen bulbs produce light when electric energy heats a small tungsten filament to high temperatures. Despite their common use in dentistry, tungsten-halogen bulbs have several disadvantages. The basic principle of light conversion by this technique is claimed to be inefficient as the light power output is less than 1% of the consumed electrical power and as they have a limited effective lifetime of approximately 100 h due to degradation of bulb components by the high heat generated [11].

The plasma arc (PAC) unit is designed for high-intensity curing of direct composite restorations and may be a time-saving alternative to tungsten-halogen curing lights [58]. As stated by the manufacturer, highly filled and pigmented composite materials can be cured in 10 s, and more transparent materials can be cured within 5 s [61]. A solid-state light-emitting diode (LED) technology was proposed in 1995 for the polymerization of light-cured dental materials to overcome the shortcomings of tungsten-halogen visible light-curing units [41]. LEDs use junctions of doped semiconductors to generate light instead of the hot filaments used in tungsten-halogen bulbs [38]. LEDs have a lifetime of over 10,000 h and undergo little degradation of output over this time. LEDs require no filters to produce blue light, are resistant to shock and vibration and take little power to operate [41]. LEDs' longer life span and more consistent light output compared with tungsten-halogen bulb technology show promise for dental applications [7].

Hosoya and Goto [20] investigated the colour changes of Silux Plus resins for 3 years, and they also investigated the influence of the light-curing times on the colour changes of Silux Plus resins over specified periods of time for 3 years; they reported that the colour differences of the resin composites increased with the time elapsed. The colour of resin composites was influenced by differences in resin shades, curing conditions, resin thickness [18–20, 32, 33, 37], background colours for colour measuring [18–20, 32, 33, 35, 37], storage methods of specimens during observation, colour measuring methods, types of colour measuring instruments [18] and observation period [20].

As a result of metamerism, the colour match between two objects perceived under one illuminant can become a mismatch under a different illuminant. To avoid these inconsistencies, the electronic devices with integrated standardized illumination can be used to measure reproducible colour parameters, which then will depend only on the angles formed between the illuminant, the object, and the detector [6, 22]. Currently, there are several electronic shade-matching instruments available for clinical use [42, 43, 63], but there are limited acceptable in vitro models for evaluating their reliability and accuracy.

The depth of cure is a very important concept in direct composite application [51]. However, adequate curing is a crucial factor in obtaining optimal physical properties and a satisfying clinical performance of a composite material. Inadequate curing diminishes the physical properties of composites, and changes in strength, stiffness, water sorption and colour stability might be expected [47]. A study similar to the current study evaluated the effects of curing units on colour changes of composites after 2 years and concluded that there were no significant differences between the colour of specimens cured with LED unit and tungsten-halogen curing unit [60]. In this previous study, the composite specimens cured with PAC unit showed significantly higher colour changes compared to tungsten-halogen and LED curing unit. After 2 years, the samples were chalky white when compared to the beginning. While the colour changes of specimens polymerized with plasma arc curing unit were visually appreciable also for the nonskilled operator (E^*_{ab}>2.5), the colour changes of specimens polymerized with tungsten-halogen and LED curing unit were not clinically relevant (E^*_{ab}<2.5) [60].

The purpose of this study was to investigate colour changes in a composite cured with selected curing units: tungsten-halogen curing unit (20 and 40 s), PAC unit (5 and 10 s) and LED unit (20 and 40 s) after 5 years. The hypothesis tested assumed that there is no difference in colour change in composite that was cured with these three curing units after 5 years.

Materials and methods

The composite used in this study was Clearfil AP-X (colour A3; Kuraray, Osaka, Japan) hybrid light-cured composite. A 10-mm diameter hole was made in a 2-mm thick teflon plate and filled with composite. The teflon plate was sandwiched between 1 mm thick glass plates and then placed on a white-coloured sheet. Glass plates flattened the composite and protected the composite from oxygen inhibition zone and standardized the irradiation distance.

Light intensity of the tungsten-halogen and LED units were measured with a radiometer (Cure Rite Efos, model 8000, range: 0–1,000 mW/cm^2; Efos Inc., Mississauga, Ontario, Canada) three consecutive times. The PAC unit produces a high light radiation that could not be read by the digital radiometer used in this study. That is why we accepted the values given in a previous study (1,190 mW/cm^2) [60]. To measure the power density received at the surface of composite, the power densities were measured at 1 mm from the end of the light guide by using 1 mm glass plates. The composite was exposed to light through the upper side plate in contact with curing light tip for: 20 or 40 s with tungsten-halogen curing unit (Hilux 550, Express Dental Products, Canada); 5 or 10 s with PAC unit (Power PAC, ADT, USA); and 20 or 40 s with LED unit (Elipar FreeLight, 3 M Espe, USA; Table 1). The plates were reversed so that the lower side of the plate was on the top. The composite was once again irradiated for the same irradiation times. Five specimens for each of the eight groups were prepared at the thickness of 2 mm and the diameter of 10 mm. No polishing techniques were used to avoid modification of the surfaces that may influence the results [17]. Specimens were stored in light-proof boxes after the curing procedure to avoid further exposure to light and stored in 37°C in 100% humidity.

Table 1 Visible light curing units studied

Brand	Type of Unit	Output of light tip (mW/cm^2)	Diameter of the tip (mm)	Applied polymerization time(s)	Manufacturer
Hilux	Tungsten-halogen	450	10	20–40	Express Dental Products, Toronto, Canada
Power PAC	PAC	1,190	6.5	5–10	ADT, San Carlos, CA, USA
Elipar Freelight	LED	380	8	20–40	3 M Espe, St. Paul, MN, USA

Colorimetric values of the specimens immediately after curing and after 5 years were measured with the Colorimeter (Minolta Chromameter, CR-300, Minolta Inc. Osaka, Japan). The measuring tip of the colourimeter was a circle of 10 mm diameter. Colour measurement was performed on consecutive tests on central parts of the specimens. Specimens were positioned at the same place on different occasions to assure consistency of the repeated measurements. A white-coloured plate, which was used for the background colour in this study, was specially made to substitute for the lining material, so that the chromatical values backed by a white-coloured plate could be considered as the colours of resin composites filled on the lining material in the oral cavity.

All specimens were chromatically measured three times and the average values calculated. Then each of five specimens of the same group was averaged and the colour difference obtained from the average colour parameters. The Comission Internationale de l'Eclairage Lab colour system was used for determination of colour difference [21]. The total colour difference, ΔE^*_{ab} between two colour stimuli, each given in terms of L^*, a^*, b^* is calculated from: [3]

$$\Delta E^*_{ab=}\left[\left(\Delta L^*\right)^2+\left(\Delta a^*\right)^2+\left(\Delta b^*\right)^2\right]^{1/2}$$

The literature is not in agreement with respect to the limit for the human eye to appreciate differences in colour considering that this limit differs from individual to individual (as it is a combination of eye characteristics and skill from the operator) [5, 26, 53]. The ΔE^*_{ab} value of 2.5 presented a borderline value recognizable by all people in a colour test [17].

The data were entered into a spreadsheet (Excel; version 4.0, Microsoft, Seattle, WA, USA) for calculation of descriptive statistics. The obtained data were analyzed by two-way analysis of variance (ANOVA) and then Tukey honestly significant difference tests (SPSS/PC, version 10.0; SPSS, Chicago, IL, USA) for comparisons among groups at the 0.05 level of significance.

Results

Colorimetric values of the composite cured with three test curing units immediately after curing and 5 years are given in Table 2.

Different curing time data with the same curing unit were pooled as no statistically significant effect of curing time was observed on colorimetric values with ANOVA (p=0.40).

In this study, a chalky white discolouration on the composite disks was observed by the naked eye, especially in the PAC unit- and LED unit-cured groups. The ΔE^*_{ab} values varied significantly depending on the curing unit used (ANOVA, p<0.01). The specimens cured with PAC unit (11.53±1.02) and LED unit (9.91±1.39) induced significantly higher colour changes than any other specimens (Tukey, p<0.01). The specimens cured with tungsten-halogen curing unit produced the lowest colour change (7.55±0.63). While there was no statistically significant difference among the colour changes of specimens cured with PAC unit and the LEDLED unit (Tukey, p=0.11), colour changes in composites photocured by the tungsten-halogen curing light were significantly different (Tukey, p<0.01).

For all study groups, while there were no differences in colour among all groups at time 0, colour differences were visually appreciable also for the nonskilled operator (ΔE^*_{ab}> 2.5) at time 5 years (Table 3). In all curing time groups, the L^* values showed a tendency to increase with the time elapsed and colours of all specimens. The a^* values showed the tendency to increase with the time elapsed; this implies the decrease in green colour factor and the increase in red colour factor. The b^* values showed a tendency to increase with the time elapsed; this implies the decrease in blue colour and the increase in yellow colour factor.

Discussion

This in vitro study measured the colour changes of specimens that were cured with each of three commercially available curing units after 5 years. The results of this study do not support the hypothesis that there is no difference in

Table 2 Material used in the study

Material	Composition
Clearfil AP-X	Barium glass, silica, colloidal silica, Bis-GMA, TEGDMA, photo-initiator silicon dioxide (71 vol%, 0.1–15 μm)

Table 3 Chromatical values immediately after curing (value 1) and after 5 years (value 2)

Curing Unit	L*	L*	a*	a*	b*	b*	ΔE
	0 year	5 year	0 year	5 year	0 year	5 year	
Tungsten-halogen							
20 s	64.30 (0.71)	67.94 (0.22)	1.66 (0.22)	6,07 (0.34)	20.17 (0.65)	25.01 (0.81)	7.65 (0.61)
40 s	62.49 (0.44)	67.59 (0.92)	1.59 (0.09)	5.36 (0.31)	17.62 (0.55)	21.59 (0.89)	7.55 (0.63)
PAC							
5 s	65.61 (0.88)	69.86 (0.69)	1.91 (0.19)	8.23 (0.76)	20.45 (0.29)	27.31 (1.03)	10.36 (0.97)
10 s	64.94 (0.55)	70.83 (1.00)	1.48 (0.24)	6.74 (0.41)	19.41 (0.64)	27.75 (0.66)	11.53 (1.02)
LED							
20 s	64.24 (0.15)	69.16 (0.30)	1.52 (0.19)	6.62 (0.52)	18.65 (0.95)	25.58 (1.11)	9.96 (1.52)
40 s	63.76 (0.59)	68.72 (0.65)	1.77 (0.24)	6.48 (0.55)	17.76 (0.46)	24.65 (0.71)	9.91 (1.39)

colour change in composite that was cured with these three curing units. There were significant differences in colour changes within groups. Under the conditions of the present study, the highest colour changes were recorded from the specimens cured with PAC unit and LED unit.

Several laboratory tests have been proposed in order to simulate and accelerate the discolouration that takes place under clinical conditions over a relatively long time [4, 50]. For this study, the samples were stored for 5 years in 37°C in water (100% humidity) and then measured for colour determination. No polishing techniques were used because the oxygen-inhibited zone might exist and influence as plus factor to resin discolouration.

A white-coloured plate, which was used for the background colour in this study, was specially made to substitute for the lining material, so that the chromatical values backed by a white-coloured plate could be considered as the colours of resin composites filled on the lining material in the oral cavity.

A study by Marais and coworkers [30] has suggested that power density (irradiance) does not have an effect on conversion of composite resin at depths beyond 2 mm; because of this, in the current study, the thickness of 2 mm was used. The samples were cured from both sides, effectively reducing thickness of resin being cured to 1 mm to get maximum conversion.

Previous investigators reported that the colour changes of composites were caused by the following factors: the chemical activator [11], resin initiator and inhibitor [44], activator progress [14], polymer quality, bisphenol A diglycidylether methacrylate (Bis-GMA) of monomer, type of filler [44], oxidation of unreacted carbon–carbon double bonds [11], heat emission of light source [55] and water [56].

A high degree of cure provides colour stability as well as hardness and strength to the material [46]. Thus a reduction in remaining double bonds to the lowest possible level is considered a desirable feature of a curing system. Inadequate polymerisation is associated with a low monomer–polymer conversion rate with a higher residual quantity of double bonds, which causes inferior physical properties, raises water absorption and solubility and leads to discolouration of the resin composite [29]. The degree of cure of a given composite is influenced by the energy density [46]. For composites, a light intensity of more than 400 mW/cm^2 is generally recommended [23]

It is conceivable that oxidation reactions of unreacted C=C double bonds produce coloured peroxide products [11]. In the present investigation, the initiation of cure by different curing units was evaluated by recording the colour changes in 5 years.

Various types of light sources were used in this study. One of these is LEDs. LEDs are being aggressively marketed; however, independent research has not yet verified the potential of this technology to replace tungsten-halogen visible light-curing units [7]. Optimal cure times for LEDs and their ability to cure all resins are still unknown [2]. A number of studies have confirmed the potential of LED technology for the light activation of dental materials. Fujibayashi [12] detected no differences in composite hardness and depth of cure between the LED and a tungsten halogen and obtained a deeper cure with the LED of 470 nm wavelength than the tungsten-halogen light at 10, 20, 40 and 60 s [12, 13], however, Polydorou concluded that the tungsten-halogen light curing unit produced higher microhardness values compared to the two LED light curing units for a standard resin composite [48]. Mills compared a light source containing 25 LEDs with a tungsten-halogen unit adjusted to an irradiance of 300 mW/cm^2 [31]. The LED unit cured composite specimens to a significantly greater depth than the tungsten-halogen unit when tested at 40 and 60 s [31]. The LED unit used in this study had 19 LEDs.

Energy density of the light-curing procedure influences the degree of conversion, depth of cure and mechanical properties of resin composites [8, 16, 24, 27, 28, 39, 45, 48, 52 ,54, 55, 62]. Power density expresses the rate of delivered photons per unit surface and thus determines the rate of free radicals generated in the composite, while exposure time, at a given power density, determines the total number of photons and thus of free radicals [36]. Since free radicals initiate polymerisation, power density and exposure time are responsible for the velocity and degree of polymerisation and thus, among others, for the mechanical properties of a given resin composite [9, 10, 45]. However, it has been suggested that there may be no benefit to polymerisation of resin composite when power density is increased above a certain value [40]. Mean power densities of the light curing units used in this study are presented in Table 1. The tungsten-halogen-based light-curing unit had a higher mean power density than the LED curing unit, and colour changes of specimens that were cured with tungsten-halogen-based curing unit was lower than LED unit. Fujibayashi (1998) demonstrated that the quality of light curing is not exclusively due to the light intensity: the narrow absorption peak of the initiator system must also be taken into account [13]. This makes the emitted spectrum an important determinant of a curing light's performance. The absorption curve of camphorquinone extends between 360 and 520 nm, with its maximum at 465 nm. It has been shown that, within this range, the optimal emission bandwidth of the light source lies between 450 and 490 nm [39].

In conventional curing devices, a major portion of the photons is emitted outside the optimal spectrum range for light curing. These photons cannot, or only with reduced probability, be absorbed by camphorquinone. In contrast, 95% of the emission spectrum of blue LEDs is situated between 440 and 500 nm. Further, the emission maximum of the blue LEDs used in this study is approximately 465 nm, which is almost identical to the absorption peak of camphorquinone. At clinically realistic irradiances, modestly greater depth of cure was found when composites were cured with an LED lamp in comparison with a tungsten-halogen lamp despite the former having a measured output approximately 70% of the latter (276 versus 388 mW/cm^2 when measured between 410 and 500 nm) [31]. Knezevic (2001) demonstrated only a minor increase in conversion degree values when 66 times stronger tungsten-halogen curing units were compared to a LED with minimal intensity of 12 mW/cm^2 [25]. This finding also supports the importance of considering the emission spectra of curing lamps relative to the absorption spectrum of camphorquinone when assessing the quality of light curing.

The PAC unit has filters that narrow the spectrum of visible light to a band centered on the 470-nm wavelength for activating part of a dual catalyst of the camphorquinone [57]. A high-energy, high-pressure ionized gas in the presence an electrical current is used to create a curing unit strong enough to increase the curing rate of composites and resin-modified glass ionomers [55]. It was pointed out that both universal hardness and depth of cure after conventional polymerization were significantly higher than those of PAC [23]. Caughman found that 3 s of light activation with a PAC is insufficient to produce maximum polymerization [1]. In the present investigation, statistically significant differences in ΔE^*_{ab} values were observed between specimens cured with tungsten-halogen curing unit and PAC unit. This is the implication that we get a lower degree of conversion when utilizing a PAC, and this may indicate that the rather narrow band of wavelengths emitted by PAC curing units is outside the range of maximum sensitivity of the camphorquinone of this composite material or curing time is not sufficient.

Differences in the composition of materials and light characteristics of light units result in significant variations of performance [39]. The results of Nomoto et al. [40]. showed that when the total amount of exposure, represented by the product of the light irradiance and the irradiation time, was kept constant, each of the depth of cure and the distributions of degree of conversion, polymeri-zation conversion and percent of pendant double bonds of light cured composite resins were the same for each material regardless of the light illuminance and irradiation time.

A study similar to the current study evaluated the effects of curing units on colour changes of composite after 2 years and concluded that there were no significant differences between the colour of specimens cured with LED unit and tungsten-halogen [60]. The composite specimens cured with PAC unit showed significantly higher colour changes compared to tungsten-halogen and LED curing unit. After 2 years, the samples were chalky white as in the present study [60]. However, in the current study, the colour changes after 5 years were evaluated, and there were some changes in the results. The specimens cured with LED unit showed more colour changes than tungsten-halogen curing unit.

It is generally thought that, according to the time elapsed, the colour of composite changes to dark colour, and yellowing occurs [17]. Like in the previous study [60], the specimens cured with different curing units revealed a colour shift from blue to yellow (positive Δb^*) and from green to red (positive Δa^*) after 5 years water storage in the present study. In this study, a chalky white discolouration on the composite disks was observed by the naked eye, especially in the PAC unit and LED unit cured groups. In this study, composite specimens were stored in 37°C in 100% humidity, and colour changes were measured. In the oral cavity, the composite surface roughly changes by mastication and other factors which are included in food deposited on the rough composite surface. In addition, the influence of heat caused by hot drinks or hot food must be considered [61]. It is possible that composite discolouration in the oral cavity might be greater than the results of this study.

Conclusion

Within the limitations of this in vitro study, the following conclusion was drawn: The composite specimens cured with tungsten-halogen showed significantly lower colour changes as compared to PAC unit and LED unit.

Conflict of interests The authors have no financial relationship with the organization that sponsored the research.

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