Spectral distribution of visible-light curing units – effect on the depth of cure in a dental composite resin

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Twelve commercial visible-light (VL) curing units were examined in order to clarify the characteristics of intensity such as illuminating power and irradiance. The results showed that all VL curing units investigated had a peak in the wavelength range 460 to 500 nm. An equation proposed by us for the relation between the integral irradiance and the depth of cure indicated a good linearity ($r = 0.997$) in the wavelength range between 460 and 480 nm when different VL curing units were used.

1. Introduction

The visible-light (VL) curing unit is used to polymerize visible-light-cured dental composite resin. For photopolymerization by the VL curing unit, VL-activated composite resins usually contain an α-diketone, such as camphorquinone, and a reducing agent to produce ion radicals [1]. The photo-sensitizer, camphorquinone, is activated in the wavelength range 400 to 500 nm [2, 3]. In general, the spectra wavelength emitted by VL units is measured in the range 400 to 550 nm [4, 5], and the depth of cure depends on the intensity of the radiation in the VL-cured resin [2, 6]. Measurements are usually taken along the direction normal to the end of the light-conductor in a VL curing unit [5, 7, 8].

Three types of light-conductor from waveguide for the dental photopolymerization source are mainly used [5]; fibre-optic cable, fibre-optic rod and glass rod. VL units may also be classified by the design, such as a gun type with a rigid light tube, and a fibre type with a flexible light tube [9].

In measuring the spectral distributions of VL units, the maximum radiant output range is found to lie between 450 and 485 nm [5]. Irradiance was also influenced by the variations in input voltage, but the fluctuation in voltage was less [10].

The depth of cure was correlated with a photocuring efficiency index in each VL-cured resin, providing the characteristics of each VL unit [5, 11]. A larger depth of photopolymerization is needed, because the composite resins in clinical restorations are not completely polymerized [12]. The depth of cure may depend on the following factors: the composition of the composite resin and the characteristics of the light unit such as the intensity, irradiation time and light transmission [13]. In this study, the properties of commercial VL curing units, such as the illuminating power and irradiance, were compared, and the depth of cure in a VL-cured dental composite resin was investigated in terms of the relation between the integral of the spectral irradiance and the depth of cure.

2. Materials and methods

Twelve VL curing units are listed in Table I. The standard light source for the VL units was a tungsten halogen lamp fitted with an integral reflector. The VL-cured dental composite resin tested was a commercial one, Occulsin (ICI, Cheshire, UK; serial no. LH06). The resin was constituted from hybrid filler type (the wt % camphorquinone contained was 1.03 ± 0.03 in the resin phase, and 0.86 ± 0.02 for a reducing agent dimethylaminoethyl methacrylate) [14]. The spectrum produced by each VL curing unit was determined by passing the light through a monochrometer (Nikon G-250, Tokyo, Japan) connected to an optical digital powermeter (Anritsu ML 93A, Tokyo, Japan).

The procedure for measurement was as follows: the fibre-optic tip or tip of the glass rod attached to the light guide was set perpendicular to the detector window of the monochrometer. The tip was positioned on an adjustable stage in order to give maximum output. The measurements were repeated three times at each setting. The spectral radiant flux, using the tabulated spectral efficiency, was then calculated. Irradiance measurements were made for electric lamp powers of 50 W for GL, 75 W for WL, FL and OL, 150 W for QL, D0, D1, D2, SL and LX, and 300 W for CA and CN as listed in Table I. The illuminating power was also obtained by measuring the spectral VL through the monochrometer with an illuminating meter (Toshiba Co., Tokyo, Japan; SPI-Type).

For the VL-activated dental composite resin, both Knoop hardness and curing efficiency were evaluated with two VL units (LX and SL). The VL curing unit (LX) is recommended for polymerizing this VL-activated resin. On a longitudinal section of the

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TABLE I Visible-light curing units

Brand name	Manufacturer	Series no.	Type	Electric power (W)	Code
Quick Light	J. Morita	1012	fibre	150	QL
Daylight Lamp	Shofu	0285741	fibre	150	D0
Daylight Lamp	Shofu	1180818	fibre	150	D1
Daylight Lamp II	Shofu	0585903	fibre	150	D2
Suncure Light	Sankin	1083	fibre	150	SL
Cure Master A	3M	04083	fibre	300	CA
Cure Master A	3M	04083	fibre	300	CN*
Luxor	ICI	06497	fibre	150	LX
Grip Light	Shofu	05850902	gun	50	GL
Wite Lite	Takara belmont	510186	gun	75	WL
Fotofil Activator Light	Johnson & Johnson	1395	gun	75	FL
Optilux	3M	03280	gun	75	OL

*Using new fibre only.

cylinder-like specimen (diameter 5 mm), which was cut with a low-speed saw ISOMET (Buehler Co., Chicago, USA), Knoop hardness was measured three times at each 1 mm depth, and the curing efficiency at a depth of 3 mm, for example, corresponded to a value at a depth between 2.05 to 3.05 mm from the surface of the resin tested. At first the thin polyethylene films, 0.05 mm thick, were set at the positions of the upper and lower surfaces in a 2 mm thick teflon block with a cavity 0.5 mm × 2 mm height. Secondly the other block with a cavity (0.5 mm × 1 mm height) was set under the first Teflon block. Visible-light was then irradiated to the resin paste within the cavity from the upper surface of the first teflon block, after setting two teflon blocks. After that, the curing efficiency $((m_d/m_b) \times 100)$ at a depth of 3 mm was calculated as follows: the cylinder-like specimen between 2.05 and 3.05 mm thick from the surface was weighed before immersing (m_b), and then immersed for 1 d in 5 ml methanol and then dried for 2 d in a desiccator and reweighed (m_d).

3. Results

Fig. 1 shows the illuminating power of the five light units indicated in Table I; the wavelength component below 400 nm was not measured, because no biological hazard is suggested below 390 nm, and the measuring range used for the wavelength was between 400 and 650 nm [2]. Peak wavelengths were found for 470 and 530 nm with five of the VL curing units, and the values of the other VL units ranged between 470 and 530 nm.

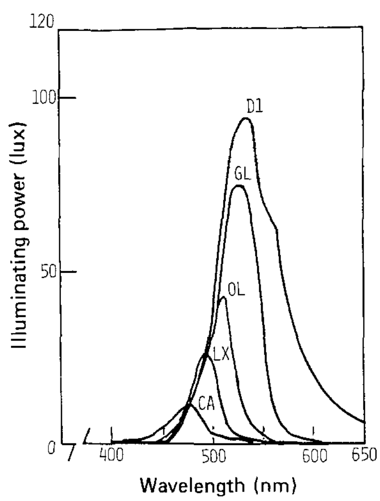

Figure 1 Illuminating power of visible-light (VL) curing units, D1, GL, OL, LX and CA.

Figs 2a, b and c show the spectral distributions of twelve VL units. The VL units were classified into three types by the characteristics of spectral distribution and peak wavelength. Three types of VL unit were described: Types 1, 2 and 3. For Type 1 the peak wavelength was about 470 nm and a small spectral distribution was found above 550 nm. For Type 3, the peak wavelength was found to be about 500 nm and the spectral distributions also ranged to above 550 nm. The VL units indicated as Type 2 were VL units which were not classified as only Type 1, or only Type 3 VL unit.

In Table II the integral irradiance values between 400 and 650 nm are indicated with the different electric lamp powers used for each of the light units. In Fig. 3a the relation between the integral values of illuminating power and irradiance for twelve VL units (Types 1, 2 and 3) is shown, and the maximum values of illuminating power and irradiance are shown in Fig. 3b. For the VL unit (Type 1), properties such as large irradiance and small illuminating power were detected. For the VL unit (Type 3) a fairly large value of illuminating power was obtained. The Type 2 VL unit was

TABLE II Integral irradiance values emitted by visible-light curing units

Electric power (W)	Code	Irradiance ($mW\,cm^{-2}$)
50	GL	230.9
75	WL	179.4
	FL	111.8
	OL	270.9
150	QL	270.4
	D0	146.6
	D1	258.4
	D2	260.8
	SL	146.6
	LX	222.7
300	CA	114.4
	CN	202.6

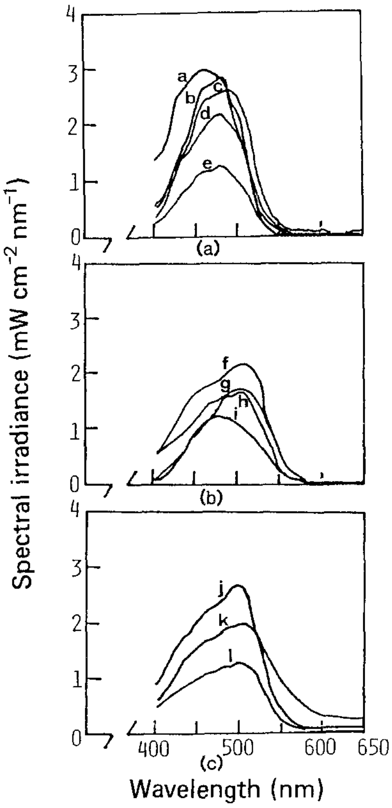

Figure 2 Spectral irradiance emitted by VL curing units: (a) Type 1 (a, OL; b, LX; c, D2; d, CN; e, CA); (b) type 2 (f; GL, g, WL; h, DO; i, FL); (c) type 3 (j, QL; k, D1; l, SL).

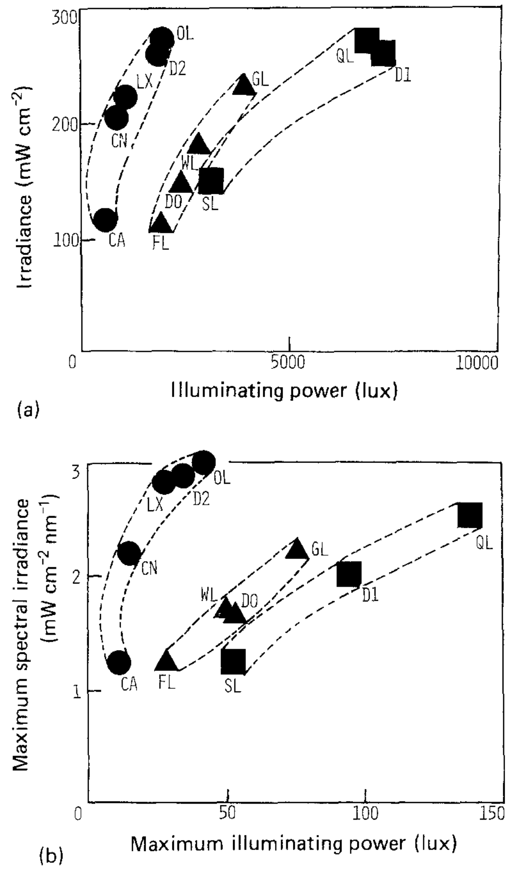

Figure 3 (a) The relation between the integral values of illuminating power and irradiance (for key, see Table I). (b) The relation between illuminating power and irradiance at a maximum value.

positioned intermediate between Type 1 and Type 3 VL units from the characteristics of VL curing unit.

For a VL-activated dental composite resin (Occulsin) the polymerization was measured at different irradiation times using different VL units, as shown in Table III (Knoop hardness) and Table IV (curing efficiency). The maximum hardness of the VL cured resin occurred at a certain depth and the value of the maximum hardness varied at different irradiation times. At a depth of 5 mm, the Knoop hardness varied for different irradiation times. The curing efficiency of the VL cured resin became larger with increasing irradiation time, at deeper depths. The maximum values of hardness after longer irradiation (40 and 60 sec) were larger than that after polymerization for 20 sec.

The variation of depth of cure with the logarithm of exposure time (irradiation time) is shown in Fig. 4 for the VL curing units (LX and SL); the relationship between depth of cure and time has been clarified by Cook and Standish [11]. The linearity was very high for each VL curing unit ($r = 0.999$ for LX, $r = 0.990$ for SL), but the relationship between the units was not found to lie on the same line. However, it is considered that the curing of the VL-activated resins is affected by the product of integral value between the spectral wavelengths and irradiation time. Figs 5 and 6 show the integral illuminating power and irradiance between 400 and 650 nm when irradiated for 20, 40, 60 sec. The relations shown in Figs 4, 5 and 6 are fairly linear using a minimum square method as indicated by the r value, but a difference between the depths of cure in the VL curing unit was found for VL curing units LX and SL. For a narrow wavelength between 460 and 480 nm, the relations shown in Figs 7a and b are,

TABLE III Knoop hardness at each depth for a visible-light cured (VL) dental composite resin (Occulsin) after irradiation with the VL units (LX and SL) for 20, 40 and 60 sec, $n = 9$ to 21

Depth (mm)	LX			SL		
	20 sec	40 sec	60 sec	20 sec	40 sec	60 sec
0.5	66.9 ± 9.3	71.9 ± 9.8	69.7 ± 8.9	47.5 ± 5.4	62.0 ± 8.0	65.4 ± 9.4
1	64.0 ± 10.0	73.6 ± 8.4	71.5 ± 15.9	49.9 ± 11.7	67.5 ± 10.1	68.6 ± 9.4
2	62.9 ± 10.4	74.4 ± 8.4	70.4 ± 9.9	32.4 ± 8.5	55.0 ± 9.9	65.6 ± 11.1
3	58.2 ± 12.1	75.6 ± 7.5	68.8 ± 11.8	28.7 ± 6.7	39.8 ± 16.8	61.6 ± 7.7
4	52.1 ± 10.8	73.4 ± 9.2	67.9 ± 7.4	27.7 ± 7.5	32.4 ± 13.0	46.5 ± 18.9
5	37.5 ± 9.9	69.9 ± 11.3	62.5 ± 9.4	*	19.0 ± 10.2	43.5 ± 17.9
6	24.6 ± 8.3	59.0 ± 9.8	40.3 ± 10.0	*	*	22.9 ± 5.5
7	19.8 ± 9.8	47.6 ± 12.6	38.1 ± 10.4	*	*	*
8	*	18.1 ± 13.3	33.4 ± 6.1	*	*	*
9	*	6.4 ± 4.5	24.0 ± 6.0	*	*	*

*Not measured.

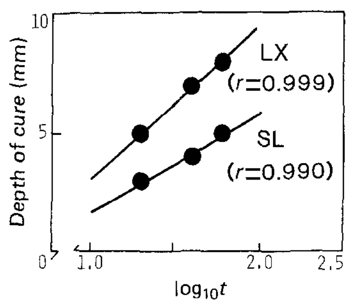

Figure 4 Variation of depth of cure with the logarithm of irradiation time (sec) for Occulsin/VL units (LX and SL).

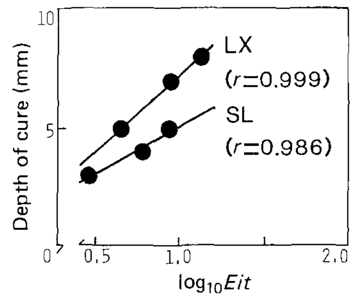

Figure 6 Dependence of depth of cure on integral irradiance emitted by VL units (LX and SL) for material (Occulsin) in the wavelength range 400 to 650 nm when irradiated for t sec.

respectively, obtained in terms of the logarithm of the integral illuminating power (Lt) and integral irradiance ($E_i t$) when irradiated for t sec, and as a result Fig. 7b shows a fairly good linearity ($r = 0.997$) between the integral value and the depth of cure, as existed on the straight line. Therefore, the depth of cure is proposed by the following equation

$$D = K_c \log_{10}(E_i t) \qquad (1)$$

where D is the depth of cure (mm), K_c a constant, E_i the integral value of irradiance between 460 and 480 nm and t the irradiation time (sec).

4. Discussion

The VL curing units investigated in this study showed a profile in the spectral distributions (Figs 1 and 2). The spectral distribution of irradiance was calculated to a 1 cm^2 area of the tip as shown in Fig. 2, because the VL unit varied significantly with the cross-sectional area of fibre-optic tip in the light-guide [7]. Although the peak wavelength of VL curing units was detected between about 460 nm and 500 nm in a spectroscopical analysis [4, 12], the spectral irradiance peak was in almost the same region as that in the above analysis, in spite of the spectral irradiance/wavelength profile measured in terms of different VL units (Fig. 2). However, there were remarkable differences in peak wavelength, ranging from 480 to 535 nm (Fig. 1), with respect to the illuminating power in VL units examined. Distinct differences were found in the irradiance when the VL units were operated at 50 to 300 W input, ranging from 111.8 to 270.9 ($mW\,cm^{-2}$) (Table II). Knoop hardness at each depth was improved by longer irradiation times in polymerizing each VL cured resin with each VL unit [7].

A comparison of the change in curing performance between VL units was not obtained [15]. According to the present study, the VL units are classified as Types 1, 2 and 3 VL units (Figs 2 and 3), and the characteristics of these VL units are more complicated than in other studies [10, 11]. In general, VL reflects from the enamel into the dentist's eye and an after-image will be produced. The illuminating power occurring then will be an important factor to consider in the cure of a VL-cured resin and to the eye. Therefore, VL units (LX and SL) showing a lower illuminating power were selected from the VL units investigated (Fig. 4). The VL curing unit of LX had a lower illuminating power and higher irradiance, and the VL curing unit (SL) showed the lowest illuminating power and the lowest irradiance of the Type 3 VL units.

The differences of Knoop hardness in every VL unit were regarded as significant using three-way analysis of variants (VL curing units, irradiation times and depth of cure) ($p < 0.01$), and then the percentage contribution to Knoop hardness was found for each factor: VL units (16.4%), irradiation times (7.2%) and depth of cure (64.6%) and others. The same significance was also found for curing efficiency in Table IV ($p < 0.01$) ((VL units; 23.4%), irradiation times (7.6%) and depth of cure (45.7%) and others).

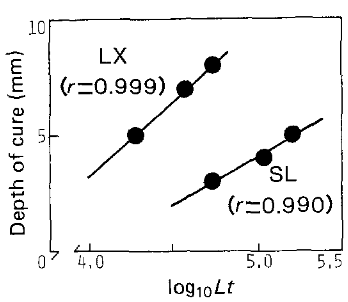

Figure 5 Dependence of depth of cure on integral illuminating power for material (Occulsin) in the wavelength range 400 to 650 nm (VL units; LX and SL) when irradiated for t sec.

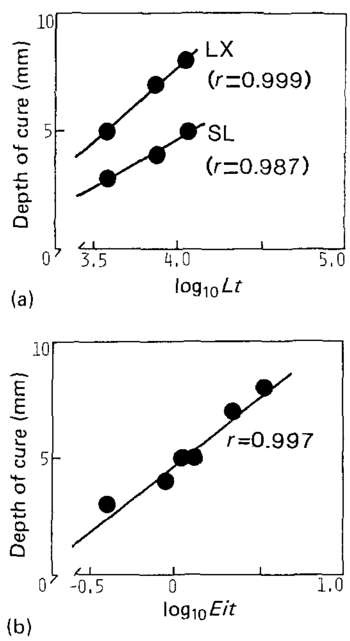

Figure 7 Plots of depth of cure in Occulsin dental composite resin against (a) integral illuminating power, and (b) integral irradiance in the wavelength range of 460 to 480 nm.

TABLE IV Curing efficiency at each depth for material (Occulsin)/VL units (LX and SL) for 20, 40 and 60 sec, $n = 3$

Depth (mm)	LX			SL		
	20 sec	40 sec	60 sec	20 sec	40 sec	60 sec
3	98.9 ± 0.6	99.5 ± 0.0	99.7 ± 0.2	92.7 ± 0.5	98.8 ± 0.4	98.7 ± 0.1
4	97.0 ± 0.4	99.4 ± 0.4	99.4 ± 0.3	72.4 ± 10.3	72.4 ± 10.3	95.5 ± 1.0
5	92.8 ± 1.0	99.5 ± 0.3	98.9 ± 0.9	54.6 ± 10.9	54.6 ± 10.9	93.4 ± 0.8
6	89.9 ± 1.0	97.8 ± 0.5	98.1 ± 0.5	*	*	83.7 ± 3.0
7	73.2 ± 3.5	94.6 ± 0.9	97.3 ± 0.4	*	*	38.7 ± 4.3
8	49.1 ± 10.8	85.1 ± 1.4	94.8 ± 0.9	*	*	*
9	*	59.6 ± 6.2	82.1 ± 5.4	*	*	*

*Not cured.

As shown in Fig. 2, the irradiance in the wavelength region 450 to 500 nm is a better indication of the effectiveness of polymerization. Namely, the photosensitizer's absorption peak at 470 nm is constituted by both a steep slope to 500 nm and a gradual trailing to 410 nm, using a 0.5 wt % solution of camphorquinone in methyl methacrylate [2]. In the wavelength region 460 to 480 nm the relation between depth of cure and the characteristics of two VL units is plotted (Figs 7a and b). The VL unit with the larger illuminating power did not necessarily show the larger irradiance, and the peak wavelength was above about 500 nm (Figs 1 and 2). On the basis of the results in Figs 1 and 2, a relationship was obtained (Figs 3a, b). At a wavelength of 460 to 480 nm, one linear relation was found between the depth of cure and the integral irradiance ($r = 0.997$) (Fig. 7b). The method in this study was a simple and reliable one with a combination of monochrometer and illuminating meter or optical powermeter, although it was difficult to measure easily the spectral distribution [2]. In addition, the reported intensity values of VL units had a different value because of the complex measuring systems [9]. On considering Equation 1, it is possible to select better VL curing units to obtain a larger depth of cure. This implies that the factors affecting the curing characteristics may be clarified by using special filters limiting the region of the wavelength in the VL curing unit. We believe that the equation proposed will be useful in considering both the curing efficiency and the depth of cure in a visible-light-cured resin.

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