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ORIGINAL ARTICLE

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Effect of power density of curing unit, exposure duration, and light guide distance on composite depth of cure

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Abstract This in vitro study compared the depth of cure obtained with six quartz tungsten halogen and light-emitting diode curing units at different exposure times and light tip-resin composite distances. Resin composite specimens (Tetric Ceram, A3; diameter 4 mm, height 6 mm) were exposed from 0-, 3-, and 6-mm distance. The curing units (200–700 mW/cm^2) were used for standard (20 and 40 s), pulse-delay mode (initial exposure of 3 s at 200 mW/cm^2, followed by a resting period of 3 min and a final exposure of 10 or 30 s at 600 mW/cm^2), or soft-start curing (40 s; exponential ramping). Curing depth was determined by measurement of Wallace hardness for each half millimeter starting at 0.5 mm from the top surface. For each specimen, a mean H_W value was calculated from the H_W values determined at the depths of 2.0 mm and less (0.5, 1.0, 1.5, and 2.0 mm, respectively). The depth of cure for each specimen was found by determining the greatest depth before an H_W value exceeding the minimal H_W value by 25% occurred. For all curing units, an increase in exposure time led to significantly higher depth of cure. Increasing the light tip-resin composite distance significantly reduced the depth of cure. With a light tip-resin composite distance of 6 mm, median values of depth of cure varied between 2.0 and 3.5 mm following a 20-s (or 3+10 s) exposure and between 3.0 and 4.5 mm following a 40-s (or 3+30 s) exposure. The composite situated above the depth of cure value cured equally well with all curing units. At both exposure times, Luxomax resulted in the significantly lowest depth of cure, and Astralis 7 yielded significantly higher depth. At both exposure times, a significant linear correlation was found between the determined power densities of the curing units and the pooled depth of cure values obtained. It seems that for the resin composite tested, the recommended exposure time of 40 s per 2-mm increment may be reduced to 20 s, or that increments may be increased from 2 to 3.5 mm. It may be that the absolute values of depth of cure found are material specific, but we believe that the relationships found between curing units, between exposure times, and between light guide distances are universal.

Keywords Halogen · Hardness · Irradiance · LED · Polymerization

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Introduction

Light-cured resin composites have become increasingly popular since their introduction in the 1970s, allowing dental restorations to be more conservative and aesthetic. The composite degree of cure is affected by power density of the curing units, the exposure time, the resin shade, the filler size, and the loading level [27]. As light passes through the bulk of the restoration, its intensity decreases greatly, thus decreasing the curing efficacy and limiting the depth of cure [32]. Power density levels are fundamental for providing an adequate depth of cure. Inadequate cure of the restoration bulk degrades physical and biological properties of the resin composite restoration [5, 9, 37]. Power density not only depends on the curing unit but also on the light tip-resin composite distance which is greatly affected in certain clinical situations.

The most widely used curing units today are quartz tungsten halogen (QTH) units. Their bulb is filled with iodine or bromine gas and contains a tungsten filament [21]. When connected to an electric current, the tungsten filament glows and produces a very powerful light [21]. White light is produced, which is then filtered to limit the output range to that of blue light (400–500 nm). However, the emitted spectrum of light is not uniformly effective for activating the photoinitiators. Heat generation is a major disadvantage of QTH units and increases with increasing radiation time [9, 33, 34]. Other drawbacks are limited lifetime of the bulb and degradation of the reflector and filter over time. One of the problems associated with photocuring resin materials is the limited depth of cure and the risk of inadequate resin conversion at depths. Several measures have been proposed to overcome insufficient conversion: long exposure times, shallow increments, application of high-intensity light sources, and post-curing. Adequate cure with QTH curing units has been found to require a power density greater than 400 mW/cm^2, a resin composite increment of maximum 2 mm, and an exposure time of 40–60 s [6, 7, 29]. However, newer curing units are more powerful and may offer greater depth of cure or reduced exposure time. Other QTH curing units feature so-called soft-start programs, e.g. two-step curing and pulse-delay curing, according to which an initial exposure at relatively low power density is followed by exposure at higher power density. The aim is to improve marginal adaptation by prolonging the phase during which the resin composite may flow and thus compensate for polymerization shrinkage and stress [2, 30, 35, 36].

To overcome some of the problems inherent to QTH units, light-emitting diode (LED) technology has been introduced in operative dentistry a few years ago [19]. In contrast to QTH units, the spectral output of gallium nitride blue LEDs falls within the maximum absorption peak of camphoroquinone (450–490 nm), the most commonly used photoinitiator [34]. Consequently, no filters are required in LED units. The power density of the first-generation LEDs was low due to limited surface area to arrange sufficient LEDs in an array. Tarle et al. [34] showed that an LED device with 9-mW/cm^2 power density was unable to adequately cure a 2-mm layer of resin composite. Dunn and Bush [10] studied the adequacy of LED units and concluded that QTH units produced significantly harder top and bottom surfaces than did LED units. Mills and Jandt [22] showed that an LED unit containing 25 blue LEDs with a power density of 290 mW/cm^2 cured hybrid composites to significantly greater depth than did a QTH unit adjusted to 300 mW/cm^2. Jandt et al. [17] compared an LED unit producing a power density of 350 mW/cm^2 with a QTH unit producing 755 mW/cm^2. Both curing units fulfilled the requirement of ISO 4049 of a depth of cure of minimum 2 mm following a 40-s exposure. The mean depth of cure of the QTH unit was about 20% higher than that of the LED unit. Newer LEDs substitute conventional LED elements with small chips that contain very large-surfaced emitting LED chips [7]. This produces higher power density and may justify reduced exposure time.

The degree of conversion of resin composites can be assessed by various methods. Direct techniques such as FTIR or Raman spectroscopy measuring in-depth differences of the degree of C=C conversion may be considered most accurate [24, 25]. However, these techniques are time-consuming and complex. Hardness measurements are widely used to evaluate resin composite cure and provide good estimation of the degree of conversion of resin composites [1, 12, 31]. Harrington and Wilson [15] reported that depth of cure is not uniform across the area of a resin composite specimen, and in order to obtain reproducible and comparative results, measurements should always be taken in the centre of the specimens.

The purpose of this study was to evaluate depth of cure of a universal resin composite cured with different QTH and LED units and/or exposure times at three light tip-resin composite distances. Three hypotheses were tested: (1) an increase in exposure time results in increased depth of cure; (2) an increase in light tip-resin composite distance results in reduced depth of cure; and (3) curing units of high power density result in higher depths of cure than do curing units of lower power density.

Materials and methods

Brass molds with a diameter of 4 mm and a height of 6 mm were used to make resin composite specimens. The molds were filled with resin composite and covered with clear Mylar strips on each side. They were placed on a white metal backing and exposed from the top surface [20]. The six different curing units studied are listed in Table 1 as are exposure times, curing modes, and power densities as determined using a hand-held dental radiometer (Optilux 100; Kerr/Demetron, Danbury, CT, USA). The Elipar Trilight was used in the soft-start mode, available only as a 40-s program: power density increases to full level during the first 15 s and remains at this level for the rest of the exposure. The Bisco VIP was used in the pulse-delay mode and started with an initial exposure of 3 s at 200 mW/cm^2, followed by a resting period of 3 min before a final exposure of 10 or 30 s at a power density of 600 mW/cm^2. Distances of 0, 3, and 6 mm between the light tip and the top surface of the specimen were tested. The resin composite used was Tetric Ceram A3 (LOT E52766, Ivoclar Vivadent, Schaan, Liechtenstein), the manufacturer of which recommended a 40-s exposure time for 2-mm-thick increments. Five specimens were made in each group. After curing, the molds were stored for 24 h in the dark at room temperature before removing the specimens, which were then stored in the dark at room temperature for 2 weeks until preparation for hardness testing. The specimens were embedded in acrylic cold mounting resin. After curing, each specimen was ground longitudinally half through the specimen. Hardness was then measured with a Wallace indentation hardness tester (H.W. Wallace, Croydon, England; serial no. C671837) at each half-millimeter depth, starting at 0.5 mm from the top surface [20]. The Wallace hardness (H_W) measures the depth of penetration of a Vickers diamond following application of an initial load of 1 g for 15 s and a test load of 100 g for 60 s. The Wallace hardness number is thus a measure of softness: the higher the H_W, the softer the material.

Table 1 Curing units included in the study

Curing unit	Type/mode	Power density (mW/cm^2)	Curing times (s)	Manufacturer
Demetron 2000 (built-in)	QTH/continuous	500	20	Demetron, Danbury, CT, USA
			40	
Astralis 7	QTH/continuous, HP mode	700	20	Ivoclar Vivadent, Schaan, Liechtenstein
			40	
Luxomax	LED/continuous	200	20	Akeda Dental, Lystrup, Denmark
			40	
Ultralume 2	LED/continuous	360	20	Ultradent Products, Inc., South Jordan, UT, USA
			40	
Bisco VIP	QTH/pulse delay	200+600	3+10	Bisco, Schaumburg, IL, USA
			3+30	
Elipar Trilight	QTH/soft start	650	40	3M/ESPE, Seefeld, Germany

Table 2 Depth of cure and maximum hardness attained (minimal H_W)

	Depth of cure (mm)				Minimal H_W (μm)	
	Mean±SD	Median	Lowest	Highest	Mean±SD	Statistics
Demetron 2000, 20 s, 0 mm	3.5±0.4	3.5	3.0	4.0	10.7±0.6	a
Demetron 2000, 20 s, 3 mm	3.5±0.4	3.5	3.0	4.0	11.5±1.3	a
Demetron 2000, 20 s, 6 mm	2.7±0.3	2.5	2.5	3.0	11.9±0.9	ab
Demetron 2000, 40 s, 0 mm	4.5±0.4	4.5	4.0	5.0	11.6±0.3	a
Demetron 2000, 40 s, 3 mm	4.1±0.4	4.0	3.5	4.5	11.2±1.0	a
Demetron 2000, 40 s, 6 mm	3.4±0.4	3.5	3.0	4.0	12.2±2.2	ab
Luxomax, 20 s, 0 mm	2.3±0.3	2.5	2.0	2.5	12.4±1.6	ab
Luxomax, 20 s, 3 mm	2.3±0.3	2.5	2.0	2.5	11.7±1.4	a
Luxomax, 20 s, 6 mm	2.1±0.2	2.0	2.0	2.5	11.4±0.8	a
Luxomax, 40 s, 0 mm	2.9±0.2	3.0	2.5	3.0	12.0±1.5	ab
Luxomax, 40 s, 3 mm	3.1±0.4	3.0	2.5	3.5	12.3±1.7	ab
Luxomax, 40 s, 6 mm	3.0±0.0	3.0	3.0	3.0	13.8±3.0	ab
Bisco VIP, 3+10 s, 0 mm	3.2±0.3	3.0	3.0	3.5	11.6±1.4	a
Bisco VIP, 3+10 s, 3 mm	2.9±0.2	3.0	2.5	3.0	11.5±0.8	a
Bisco VIP, 3+10 s, 6 mm	3.0±0.0	3.0	3.0	3.0	13.4±1.7	ab
Bisco VIP, 3+30 s, 0 mm	4.1±0.2	4.0	4.0	4.5	11.6±1.0	a
Bisco VIP, 3+30 s, 3 mm	4.1±0.4	4.0	3.5	4.5	12.1±1.4	ab
Bisco VIP, 3+30 s, 6 mm	3.9±0.4	4.0	3.5	4.5	12.3±1.3	ab
Astralis 7, 20 s, 0 mm	3.9±0.4	4.0	3.5	4.5	14.4±2.2	ab
Astralis 7, 20 s, 3 mm	4.0±0.0	4.0	4.0	4.0	15.5±1.5	b
Astralis 7, 20 s, 6 mm	3.5±0.5	3.5	3.0	4.0	13.2±2.8	ab
Astralis 7, 40 s, 0 mm	4.8±0.3	5.0	4.5	5.0	11.6±0.8	a
Astralis 7, 40 s, 3 mm	4.8±0.3	5.0	4.5	5.0	11.8±1.8	a
Astralis 7, 40 s, 6 mm	4.3±0.3	4.5	4.0	4.5	14.0±2.6	ab
Ultralume 2, 20 s, 0 mm	3.1±0.4	3.0	2.5	3.5	11.9±0.9	ab
Ultralume 2, 20 s, 3 mm	2.9±0.2	3.0	2.5	3.0	13.8±1.5	ab
Ultralume 2, 20 s, 6 mm	2.8±0.3	3.0	2.5	3.0	13.4±1.3	ab
Ultralume 2, 40 s, 0 mm	4.1±0.4	4.0	3.5	4.5	12.6±1.0	ab
Ultralume 2, 40 s, 3 mm	3.8±0.3	4.0	3.5	4.0	11.5±0.8	a
Ultralume 2, 40 s, 6 mm	3.5±0.4	3.5	3.0	4.0	12.9±1.7	ab
Elipar Trilight, 40 s, 0 mm	4.4±0.2	4.5	4.0	4.5	10.8±0.7	a
Elipar Trilight, 40 s, 3 mm	4.2±0.6	4.0	3.5	5.0	13.0±1.7	ab
Elipar Trilight, 40 s, 6 mm	3.8±0.3	4.0	4.5	4.0	11.0±0.8	a

Effect of curing unit, exposure time, and distance between light tip and resin composite (n=5). For all 32 minimal H_W values, values characterized by same letter are not statistically different at $\alpha \leq 0.05$

Determination of depth of cure

For each specimen, a mean H_W value was calculated from the H_W values determined at the depths of 2.0 mm and less (0.5, 1.0, 1.5, and 2.0 mm, respectively) [20]. These values are shown in Table 2 as "minimal H_W" values. The depth of cure for each specimen was then found by determining the greatest depth before an H_W value exceeding the minimal H_W value by 25% occurred. The choice of a 25% increase in H_W as determinant for the depth of cure was based on the following considerations. With a mean coefficient of variation of 12.3% in this study, an H_W value exceeding the minimal H_W by 25% is two standard deviations distant from the mean. This location implies that the probability of this value not being higher than the mean is less than around 2.5% [20].

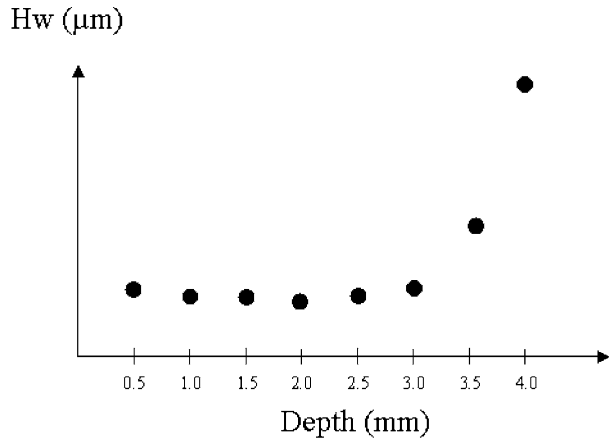

Fig. 1 Wallace hardness (H_W) of a representative resin composite specimen at increasing depth from the top surface

Statistical analyses

Parametric as well as non-parametric statistical tests were used to analyze the results. Normally distributed data with homogeneous standard deviations were analyzed by Student's *t*-test, one-way ANOVA, and, in case of statistical differences, by Newman–Keuls' multiple range test [3]. Remaining data were analyzed by Kruskal–Wallis H-test [3]. A pre-set level of significance of 0.05 was used.

Results

Figure 1 shows the results of a typical series of H_W measurement. In no case was a significant increase in H_W found until a depth of more than 2.0 mm was reached. The minimal H_W values shown in Table 2 were compared simultaneously for all distances, exposure times, and curing units. It should be born in mind that H_W really is a measure of softness, i.e. the higher the value of H_W, the softer is the resin composite. The standard deviations were made homogeneous by logarithmic transformation [14]. The differences in minimal H_W were minor, and generally, there were no significant differences among the distances, exposure times, nor the curing units. However, the high minimal H_W value for the Astralis 7 curing unit, observed with 20-s exposure from a distance of 3 mm, resulted in significant differences between the Astralis 7 curing unit and Demetron 2000, Luxomax, and Bisco VIP, respectively, for this specific distance and exposure time.

Because of lack of homogeneity of the standard deviations, the depth of cure data was analyzed by non-parametric statistics. For all curing units except Elipar Trilight, statistically significant differences were found among the six (or three for Elipar Trilight) mean values of depth of cure. Generally, prolonged curing yielded higher depth of cure values, and a statistical analysis of the *increases* in depth of cure obtained as a result of prolonged curing showed that prolonged curing significantly increased the depth of cure (P<0.0005). Generally, higher depth of cure values was obtained when there was no distance between the curing tip and the resin composite surface. A statistical analysis of the *differences* in depth of cure between 0- and 3-mm and between 3- and 6-mm tip distances, respectively, showed that increasing the distance significantly reduced the depth of cure (P<0.0005). In order to compare the curing units, the depth of cure values at 0 mm (n_i=5) was pooled with those at 3 mm (n_i=5) and at 6 mm (n_i=5) for each curing unit and exposure time (i.e. n_i=15). The obtained mean values and standard deviations fulfilled the prerequisites for use of parametric statistical methods, and the mean values were compared by one-way ANOVA followed by Newman–Keuls' multiple range tests. For the Bisco VIP curing unit, the exposure times of 3+10 and of 3+30 s were compared with exposure times of the other curing units of 20 and 40 s, respectively. At an exposure time of 20 s, the curing units fell into three groups: Luxomax resulted in the significantly lowest depth of cure, Demetron 2000, Ultralume 2, and Bisco VIP yielded higher and statistically similar depths of cure, and Astralis 7 yielded the significantly highest depth of cure. At an exposure time of 40 s, Luxomax resulted in the significantly lowest depth of cure, and Astralis 7 yielded significantly higher depth of cure than did Luxomax and Ultralume 2. At both exposure times, a significant linear correlation was found between the determined power densities of the curing units (Table 1) and the pooled depth of cure values obtained (20 s, r=0.92, P<0.025; 40 s, r=0.94, P<0.005).

Discussion

An increasing number of types of curing units are available today. Besides conventional QTH units, there are programmable and/or high-intensity QTH units, plasma arc, and LED curing units. The high-intensity QTH units were intended to allow for shorter exposure times per increment. However, curing units of similar power density values can result in different depths of cure due to differences in the spectrum of the emitted light. Also, different resin composites may cure to different extents. Because of the large variety in resin composites, curing units, and curing regimes, it is difficult to track all the proper combinations. Hence, to assess the effectiveness of the curing units studied, the resin composite was standardized by using a universal hybrid resin composite of a commonly used shade (Tetric Ceram shade A3).

One factor known to influence depth of cure is exposure time. As expected, 40-s exposures (3+30 s for Bisco VIP) led to significantly higher depths of cure than did 20-s exposures (3+10 s for Bisco VIP) for all curing units, and the first hypothesis was therefore accepted.

Light energy is absorbed as the light passes through air [21, 28]. Harrington and Wilson [15] found that the power density at the resin composite surface decreased to approximately one third, when the light tip was held at a distance of 7 mm from the resin composite surface instead of in close contact with the resin composite. Meyer et al. [21] observed that LED curing units showed a significant decrease in power density when the light tip-resin composite distance was increased. Price et al. [26] reported that the mean distance of the light tip to the gingival floor of Class II molar cavities was 6.3 mm. In the present study, we evaluated light tip-resin composite distances of 0, 3, and 6 mm. The highest depths of cure were found when the tip distance was 0 mm. Increases in distance from 0 to 3 and from 3 to 6 mm, respectively, significantly reduced the depths of cure. Light dispersion can be a major factor as to the changes in the calculated depth of cure. The second hypothesis was therefore validated. When determining the exposure time appropriate in a given clinical situation, the practitioner therefore also needs to consider the significance of a possible distance between the light tip and the resin composite surface.

Despite lower power density as registered by the hand-held radiometer, the LED unit Ultralume 2 (360 mW/cm^2) showed statistically similar depths of cure as the QTH units Demetron 2000 (500 mW/cm^2) and Bisco VIP (200 and 600 mW/cm^2) for both exposure times at all three distances. This finding is in agreement with that of Hofmann et al. [16] and may be explained by the fact that the higher power density registered for QTH units includes spectral ranges that are not well absorbed by camphoroquinone [8, 21]. The second LED device, Luxomax, with a power density of 200 mW/cm^2, showed the significantly lowest depth of cure of all curing units studied. The poor result corroborates the finding of Meyer et al. [21] who reported that the power density at the top surface of a restoration cured with Luxomax was only 40% of that of other marketed LED devices.

Despite differences in emission spectrum between QTH and LED curing units and between different brands of curing units within each category, a significant, positive correlation was found between the measured power densities of the QTH and LED curing units and the depths of cure. The third hypothesis was therefore accepted. Thus, differences in power density did not result in differences in degree of conversion of the optimally cured resin composite material, as determined by hardness measurements, but in different depths of cure. This result is in agreement with previous findings [20, 23, 26] and corroborates the finding of Rueggeberg et al. [29] that power densities between 233 and 800 mW/cm^2 resulted in the same degree of cure of the top surface.

Studies have proposed various soft-start curing techniques in an attempt to improve marginal adaptation of resin composite restorations through reduced conversion rate and curing stress formation [30, 35]. Cunha et al. [8] measured Knoop hardness at depths of 0, 1.5, 2.5, 4.0, and 5 mm after a 40-s continuous exposure (520 mW/cm^2) and after a two-step exposure (10 s at 150 mW/cm^2 followed by 30 s at 520 mW/cm^2) and found no significant differences between the two curing techniques at any depth. Other studies have shown the hardness obtained on top and bottom surfaces not to differ between continuous exposures and stepped exposures [4, 11, 36]. In corroboration of these previous results, the soft-start curing technique of the Elipar Trilight showed similar depths of cure as did 40-s continuous exposures with the Ultralume 2 and Demetron 2000 units. The other soft-start technique, the pulse-delay technique advocated for curing of the last, top composite increment [18], resulted in a depth of cure statistically similar to the continuous exposure with the Ultralume 2 and Demetron 2000 units at comparable exposure duration and light tip distances. This result contrasts that of Hackman et al. [13], who reported a remarkably low conversion at the top surface, which diminished rapidly at depths. However, Rueggeberg et al. [31] reported that hardness values from the top surface and to a depth of 2 mm obtained with a pulse-delay technique were equivalent to those obtained with a conventional continuous QTH cure. Past this depth, the pulse-delay technique showed inferior curing.

It can be concluded that all curing units used in this study were able to cure more than the recommended 2-mm depth despite a light tip distance of up to 6 mm and an exposure duration as low as 20 s. Increasing the light tip-resin composite distance or decreasing the exposure time decreased the depth of cure. With a distance of 6 mm and an exposure duration of 20 s, the median depth of cure was found to vary between 2.0 and 3.5 mm and with an exposure time of 40 s between 3.0 and 4.5 mm. Based on the results of the present study, it seems that, for the resin composite tested, the exposure time per 2-mm increment may be reduced from the 60 s generally recommended to 20 s, and that with a 40-s exposure time, the increment thickness can be increased to 3.5 mm. It may be that the absolute values of depth of cure found are material specific, but we believe that the relationships found between curing units, between exposure times, and between light guide distances are universal.

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References

1. Asmussen E (1982) Restorative resins: hardness and strength vs quantity of remaining double bonds. Scand J Dent Res 90:484–489

2. Asmussen E, Peutzfeldt A (2001) Influence of pulse-delay curing on softening of polymer structures. J Dent Res 80:1570–1573
3. Bruning JL, Kintz BL (1997) Computational handbook of statistics. Longman, New York
4. Burgess JO, Walker RS, Porche CJ, Rappold AJ (2002) Light curing—an update. Comp Cont Ed 23:889–906
5. Caughman WF, Caughman GB, Shiflett RA, Rueggeberg F, Schuster GS (1991) Correlation of cytotoxicity, filler loading and curing time of dental composites. Biomaterials 12:737–740
6. Caughman WF, Rueggeberg FA, Curtis JW (1995) Clinical guidelines for photocuring restorative resins. J Am Dent Assoc 126:1280–1286
7. Caughman WF, Rueggeberg FA (2002) Shedding new light on composite polymerization. Oper Dent 27:636–638
8. Cunha LG, Sinhoreti MA, Consani S, Sobrinho LC (2003) Effect of different photoactivation methods on the polymerization depth of a light-activated composite. Oper Dent 28:155–159
9. Davidson CL, Feilzer AJ (1997) Polymerization shrinkage and polymerization shrinkage stress in polymer-based restoratives. J Dent 25:435–440
10. Dunn WJ, Bush AC (2002) A comparison of polymerization by light emitting diode and halogen-based light curing units. J Am Dent Assoc 133:335–341
11. Feilzer AJ, Dooren LH, de Gee AJ, Davidson CL (1995) Influence of light intensity on polymerization shrinkage and integrity of restoration–cavity interface. Eur J Oral Sci 103:322–326
12. Ferracane JL (1985) Correlation between hardness and degree of conversion during the setting reaction of unfilled dental restorative resins. Dent Mater 1:11–14
13. Hackman ST, Pohjola RM, Rueggeberg FA (2002) Depth of cure and effect of shade using pulse-delay and continuous exposure photo-curing techniques. Oper Dent 27:593–599
14. Hald A (1952) Statistical theory with engineering applications. Wiley International Edition, New York
15. Harrington E, Wilson HJ (1993) Depth of cure of radiation-activated materials—effect of mould material and cavity size. J Dent 21:305–311
16. Hofmann N, Hiltl O, Hugo B, Klaiber B (2002) Guidance of shrinkage vectors vs irradiation at reduced intensity for improving marginal seal of class V resin-based composite restorations in vitro. Oper Dent 27:510–515
17. Jandt KD, Mills RW, Blackwell GB, Ashwoth SH (2000) Depth of cure and compressive strength of dental composites cured with blue light emitting diodes (LEDs). Dent Mater 16:41–47
18. Kanca J, Suh BI (1999) Pulse activation: reducing resin-based composite contraction stresses at the enamel cavosurface margins. Am J Dent 12:107–112
19. Knezevic A, Tarle Z, Meniga A, Sutalo J, Pichler G, Ristic M (2001) Degree of conversion and temperature rise during polymerization of composite resin samples with blue diodes. J Oral Rehabil 28:586–591
20. Lindberg A, Peutzfeldt A, van Dijken JWV (2004) Curing depths of a universal hybrid and flowable resin composite cured with quartz tungsten halogen and light-emitting diode units. Acta Odontol Scand 62:97–101
21. Meyer GR, Ernst C-P, Willershausen B (2002) Decrease in power output of new light-emitting diode (LED) curing devices with increasing distance to filling surface. J Adhes Dent 4:197–204
22. Mills RW, Jandt KD, Asworth SH (1999) Dental composite depth of cure with halogen and blue light emitting diode (LED) technology. Br Dent J 186:388–391
23. Park SH, Krejci I, Lutz F (2002) Microhardness of resin composites polymerized by plasma arc or conventional visible light curing. Oper Dent 27:30–37
24. Peutzfeldt A, Asmussen E (2000) The effect of postcuring on quantity of remaining double bonds, mechanical properties, and in vitro wear of two resin composites. J Dent 28:447–452
25. Pianelli C, Devaux J, Bebelman S, Leloup G (1999) The micro-Raman spectroscopy, a useful tool to determine the degree of conversion of light-activated composite resins. Biomed Mater Res 48:675–681
26. Price RB, Dérand T, Sedarous M (2000) Effect of distance on the power density from two light guides. J Esthet Dent 12:320–327
27. Rueggeberg FA, Caughman WF, Curtis JW, Davis HC (1993) Factors affecting cure at depths within light-activated resin composites. Am J Dent 6:91–95
28. Rueggeberg FA, Jordan DM (1993) Effect of light-tip distance on polymerization of resin composite. Int J Prosthodont 6:364–370
29. Rueggeberg FA, Caughman WF, Curtis JW Jr (1994) Effect of light intensity and exposure duration on cure of resin composite. Oper Dent 19:26–32
30. Rueggeberg FA, Caughman WF, Chan DN (1999) Novel approach to measure composite conversion kinetics during exposure with stepped or continuous light-curing. J Esthet Dent 11:197–205
31. Rueggeberg FA, Ergle JW, Mettenburg DJ (2000) Polymerization depths of contemporary light-curing units using microhardness. J Esthet Dent 12:340–349
32. Ruyter IE, Öysaed H (1982) Conversion in different depth of ultraviolet and visible light activated composite materials. Acta Odontol Scand 40:179–192
33. Shortall AC, Harrington E (1998) Temperature rise during polymerization of light-activated resin composites. J Oral Rehabil 25:908–913
34. Tarle Z, Meniga A, Knežević A, Šutalo J, Ristić M, Pichler G (2002) Composite conversion and temperature rise using a conventional, plasma arc, and an experimental blue LED curing unit. J Oral Rehabil 29:662–667
35. Uno S, Asmussen E (1991) Marginal adaptation of a restorative resin polymerized at reduced rate. Scand J Dent Res 99:440–444
36. Unterbrink GL, Muessner R (1995) Influence of light intensity on two restorative systems. J Dent 23:118–183
37. Venhoven BAM, de Gee AJ, Davidson CL (1993) Polymerization contraction and conversion of light-curing BisGMA-based methacrylate resins. Biomaterials 14:871–875