Visible-light curing units: correlation between depth of cure and distance between exit window and resin surface

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Study 1) The depth of proximal cavities was measured on previously taken bitewing radiographs. Study 2) By means of a scrape test, the relationship between depth of cure and irradiation distance was examined with four different curing units and two different restorative resins. Study 3) The microhardness of one of the polymerized resins was measured 0.5 mm below the free surface of the filling and then at 1.0 mm, 1.5 mm, 2.0 mm, and so forth until the resin became so soft that no hardness could be recorded. The hardness at each 0.5-mm level was recorded in relation to irradiation distance. 1) The cavity depth was most often 4–5 mm in lower premolars, 5–6 mm in upper premolars and lower molars, and 5–7 mm in upper molars. In the latter teeth, 15% of the cavities were $\geq$8 mm deep. 2 and 3) The depth of cure decreased moderately and in a linear manner with increasing irradiation distance. An irradiation distance of 12 mm reduced the depth of well-cured resin only by about 1 mm as compared with close contact between exit window and surface of resin. □ *Dental materials; polymerization; restorative resins*

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Layering of light-activated composites is a must in deep cavities to obtain a sufficient degree of conversion. Another rationale for using an incremental technique is that layering of the restorative resin reduces the polymerization shrinkage and thereby the risk of cuspal flexure and marginal gaps (1–4). It is, however, impossible to get close contact between the exit window of the lamp and the first increment when using a layering technique in the proximal part of class-II cavities. This problem has been identified by several authors, and a not infrequent citation in the dental literature has been that the loss of light intensity of curing units follows the 'law of inverse square'. Also, quite a few manufacturers are producing thin, light-guiding rods for polymerization of composites in proximal cavities and marketing these special light-tips on the basis of the demand for the exit window being as close as possible to the restorative resin.

Moseley et al. (5) studied the intensity loss of curing units versus distance between exit window and resin and found that the loss of intensity was linear. We found in a later study (6) that a microfilled composite was cured to a depth of 4.1 mm with close contact between resin and exit window of the lamp tested (both well-cured and insufficiently cured resin); but the total curing depth was only reduced from 4.1 to 2.7 mm when the irradiation distance was increased to 18 mm.

The purpose of the present study was 1) to measure the depth of proximal cavities in upper and lower premolars and molars, 2) to examine the relationship between depth of cure and irradiation distance with different restorative resins and different lamps, and 3) to measure the microhardness and the proportion of well-cured resin versus depth of cure.

Materials and methods

Study 1

The depth of the proximal part of class-II amalgam fillings was measured on previously taken bitewing radiographs from 100 adult patients treated by 20 different dentists. On these bitewings, a light-guiding rod with a diameter of 8 mm (Visilux 2, 3M, St. Paul, Minn., USA) was placed as close as possible to the occlusal part of the proximal amalgam filling until 'contact' was obtained with one of the cusps on the radiograph. The distance between the exit window of the light rod and the bottom of the proximal cavity was then measured with a periodontal probe (2-mm gradings; reading accuracy, <1 mm). Third molars were not included.

Study 2

Cavities were prepared in extracted human molars without caries lesions and/or fillings. The cavities were cylindrical with a diameter of approximately 4 mm and a depth of 7–10 mm (the cavity went through the tooth in the upper third of the crown from the lingual surface to the buccal surface). The cavity was filled with one of the composites mentioned later, covered with a matrix (3M), and irradiated for 40 sec. The distance between the exit window of the lamp and the surface of the resin was 0, 2, 4, 6, 9, 12, 18, or 30 mm. The rationale for using distances of 18 and 30 mm, which are not clinically relevant, was to get a more comprehensive understanding of the relationship between irradiation distance and depth of cure.

The light sources used were Coltolux II (Coltene, Altstätten, Switzerland), LC-80 (Lysta, Farum, Denmark), Translux CL (Kulzer, Wehrheim, Germany), and Visilux 2 (3M). Each unit was tested with the universal shade of a hybrid urethane-based restorative (Ful-fil, Dentsply, Konstanz, Germany) and a microfilled BisGMA-based composite (Silux Plus, 3M). Here, Silux Plus will be referred to as Silux.

Five minutes after irradiation the occlusal surface of the tooth was ground flat on wet carborundum paper no. 220 (Struers A/S, Copenhagen, Denmark) until the composite was exposed. The uncured resin was then scraped off, and the remaining hard material was measured with a slide gauge (reading accuracy, 0.05 mm). The method applied will be discussed later. With all four curing units, four test specimens were measured at each of the eight distances (0, 2, 4, 6, 9, 12, 18, and 32 mm).

The relationship between the irradiation distance and the depth of cure was analyzed by linear regression. The various combinations of lamp and resin were also analyzed as to differences between regression coefficients a and between regression coefficients b (7). Regression coefficient a = depth of cure with close contact between light tip and matrix. Regression coefficient b = how much the depth of cure was reduced with increased irradiation distance. The significance level was set to 5%.

Study 3

The size of the cavities was the same as that used in study 2. Only one restorative resin and one lamp was tested (Silux cured with a Visilux 2 unit). The restorative resin was irradiated with a distance between the exit window and the resin surface of 0, 6, or 12 mm (10 test specimens in each group). After being stored at room temperature for 7 days, the teeth were ground flat to expose the polymerized filling. The hardness of the resin was then measured with a microindentation tester mounted in a Reichert MeF Universal Camera Microscope (Vienna, Austria, 8 × 63) with a measuring ocular. The hardness of the resin was first measured 0.5 mm below the free surface of the filling and then at 1.0 mm, 1.5 mm, 2.0 mm, and so forth, until the resin became so soft that no hardness could be recorded.

The mean hardness of the resin for each 0.5-mm step was calculated on the basis of three measurements.

Differences between the hardness of the irradiated resin versus depth of measurement were analyzed with the Newman–Keuls multiple-range test (8). The significance level was set to 5%.

Table 1. Proximal cavity depth in posterior teeth (distance between light tip and bottom cavity)

Teeth*	Percentage distribution of cavity depth					
	3 mm	4 mm	5 mm	6 mm	7 mm	≥8 mm
Lower premolars	3	38	34	16	6	2
Upper premolars	1	14	50	24	8	3
Lower molars	1	16	34	31	10	8
Upper molars	–	5	26	30	24	15

* Third molars were not included.

Results

Study 1 (cavity depth)

The depth of 1146 proximal cavities was measured: 204 lower premolars, 304 upper premolars, 355 lower molars, and 283 upper molars. The depth of the proximal cavities are shown in Table 1.

The distance between the exit window of the light-tip and the bottom of the proximal cavities was mostly 4–5 mm in lower premolars (72%), 5–6 mm in upper premolars and lower molars (74% and 65%, respectively), and 5–7 mm in upper molars (80%).

A distance of 8 mm or more was found in 2–3% of the cases for premolars, whereas 8% of the lower molars had a proximal depth of ≥8 mm. As to upper molars, the distance between the exit window and the bottom of the proximal cavity was ≥8 mm in 15% of the cases.

Study 2 (depth of cure versus irradiation distance; scrape test)

The correlations between depth of cure and irradiation distance are presented in Figs. 1–4, which also give the linear regressions lines. The coefficients of correlation varied between −0.86 and −0.97.

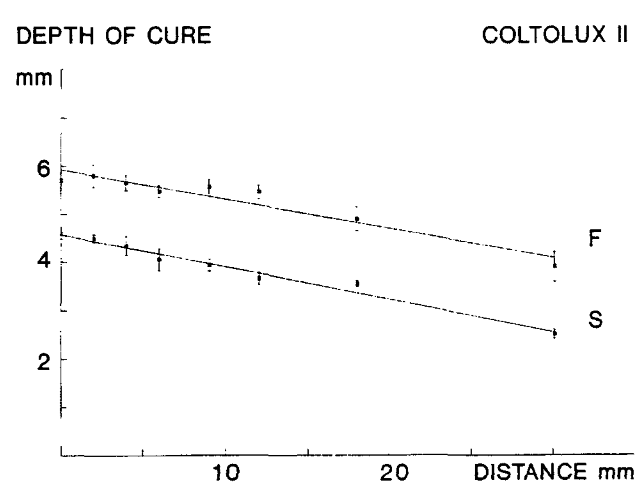

Fig. 1. Coltolux II: relation between depth of cure and irradiation distance; mean and one standard deviation. F = Ful-fil; S = Silux Plus.

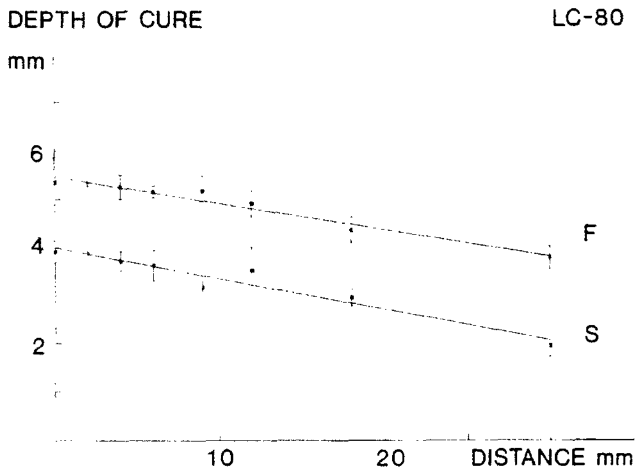

Fig. 2. LC-80: relation between depth of cure and irradiation distance; mean and one standard deviation. F = Ful-fil; S = Silux Plus.

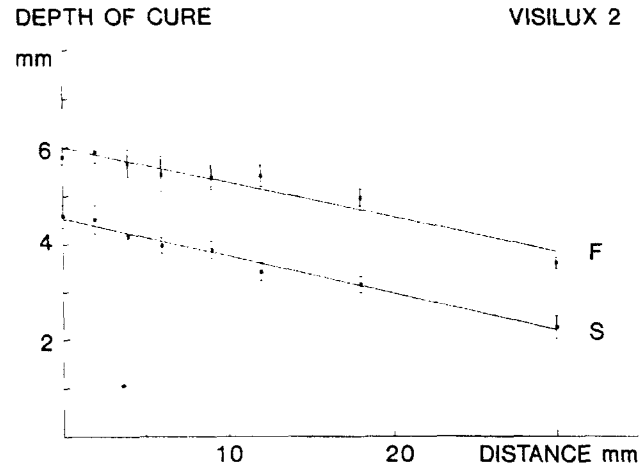

Fig. 4. Visilux 2: relation between depth of cure and irradiation distance; mean and one standard deviation. F = Ful-fil; S = Silux Plus.

Analyses of regression coefficient *a* (depth of cure with close contact between light-tip and matrix) ranked the lamps in order of decreasing effectiveness as follows: Translux CL > Coltolux II = Visilux 2 > LC-80.

As to regression coefficient *b*, there was no statistically significant difference between the slope of the eight regression lines ($P = 0.76$) (Figs. 1–4); that is, both resins had, with all four curing units, the same reduction in the depth of cure with increased irradiation distance. With an irradiation distance of 12 mm the depth of cure was reduced by 0.8 mm.

Study 3 (depth of cure versus irradiation distance; microhardness)

The decrease in microhardness of the irradiated resin could be divided into two parts: a slow one in the upper part of the resin and a pronounced, more rapid one in the deeper part (Fig. 5).

For each of the 3 × 10 test specimens, differences between the hardness of the irradiated resin versus the depth of measurement were analyzed with the Newman–Keuls multiple-range test (8). This analysis showed that a statistically significant difference between the microhardness measured 0.5 mm below the free surface and that measured deeper was found at a level of 4.2 ± 0.6 mm with close contact between resin and exit window (mean and standard deviation of 10 test specimens). With an irradiation distance of 6 mm this difference was found at a level of 3.7 ± 0.5 mm, and with a distance of 12 mm at 3.4 ± 0.4 mm. Analyses of variance (8) showed that, irrespective of the irradiation distance, there was no statistically significant difference between the microhardness down to a depth of 3.0 mm ($P > 0.05$).

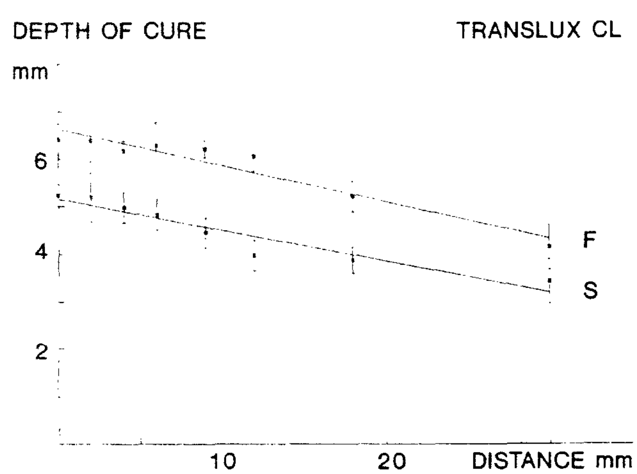

Fig. 3. Translux CL: relation between depth of cure and irradiation distance; mean and one standard deviation. F = Ful-fil; S = Silux Plus.

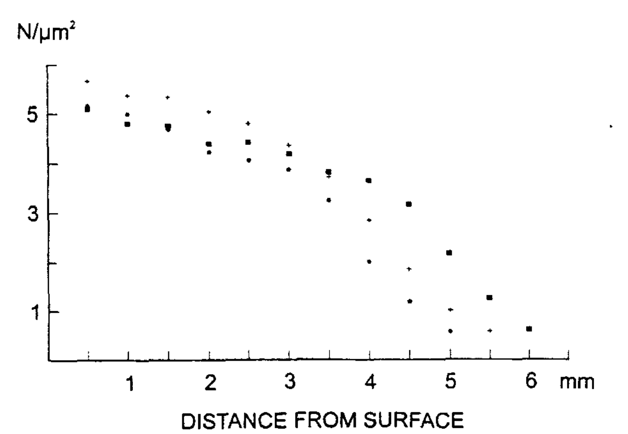

Fig. 5. Mean microhardness of Silux Plus (newton/μm^2) in relation to depth of measurement. Irradiation distance: square = 0 mm; cross = 6 mm; star = 12 mm.

The total depth of cure, both well-cured and insufficiently cured resin, was estimated by linear extrapolation based on regression analyses in which the four deepest measuring points were used (Fig. 5). With close contact between the light tip and the matrix the depth of cure was 6.3 mm, whereas it was 5.8 mm with an irradiation distance of 6 mm and 5.2 mm with an irradiation distance of 12 mm—that is, a reduction of 1.1 mm from close contact to a distance of 12 mm.

Discussion

The cavity depth in the proximal part of class-II cavities varied pronouncedly, with lower premolars having the smallest depth and upper molars the largest one (Table 1); 15% of the latter teeth had a cavity depth $\geq$8 mm, which means that several of the cavities measured had an apical wall that was beyond the enamel–cementum junction.

As mentioned in the introduction, Moseley et al. (5) found that the reduction of intensity was linear with the distance between the exit window and the surface of resin composite. Our study did not measure light intensity but showed that increased distance was only reflected to a moderate extent in the depth of cure. Furthermore, we found that the depth of cure did not follow a law of inverse square but was reduced in a linear manner with increasing distance between light-tip and composite surface.

The relation between light intensity and distance of light-tip is dependent on several factors, one of which is degree of divergence of the light beam leaving the exit window. With a completely parallel beam, the loss of intensity is minimal, whereas a highly diverging beam would give rise to significant reductions in intensity with distance. It seems obvious that depth of cure should diminish with decreasing light intensity, but several factors are at play in the determination of this relationship. In light-curing materials the irradiation produces free radicals, which in their turn cause growth of polymer chains. The light penetrates the upper part of the resin, but absorption in the material prevents the light from reaching the deeper parts. The free radicals generated in the upper parts initiate polymerization, but the polymerization will not propagate in depth beyond a certain limit, so that the deeper sections of the resin remain unpolymerized. The minimum concentration of free radicals necessary to give rise to polymerization is not known, but the relation to irradiation distance may be estimated as follows. According to the law of Lambert–Beer, one may assume that

$$l_d = l_0 \cdot \exp(-\alpha \cdot d)$$

where l_d is the intensity of light at depth *d* from the resin surface; l_0 is the intensity of light at the resin surface with zero distance to the light-tip; $\exp(-\alpha \cdot d)$ is $e^{(-\alpha \cdot d)}$, and α is a constant. The intensity of light at the resin surface (l_0) depends on the distance to the light-tip. If we assume with Moseley et al. (5) that this dependence is linear, we may write

$$l_0 = l_e \cdot (1 - \beta \cdot D)$$

where l_e is the intensity of light at the exit window, β is a constant, and D is the distance between the light tip and the resin surface. Combining the two equations to eliminate l_0, we get

$$l_d = l_e \cdot (1 - \beta \cdot D) \cdot \exp(-\alpha \cdot d)$$

Now we may assume a depth d_{max} below which the resin is not polymerized. The corresponding minimum intensity of light is l_{min}. If it is assumed that $\beta \cdot D$ is small compared with 1 (which amounts to assuming that the intensity of light is only moderately reduced with distance D), by rearranging, and by inserting l_{min} and l_d, we get

$$\mathrm{logn} l_{min} = \mathrm{logn} l_e - \beta \cdot D - \alpha \cdot d_{max}$$

or

$$\alpha \cdot d_{max} = \mathrm{logn} l_e - \mathrm{logn} l_{min} - \beta \cdot D,$$

showing that the depth of cure d_{max} decreases linearly with distance D of the light-tip. Accordingly, the observed dependence of depth of cure may be explained on the basis of a few reasonable assumptions.

The scrape test used in study 2 (Figs. 1–4) does not distinguish between optimally cured and inadequately cured resin (9–11). The reason for getting an 0.8-mm reduction of total curing depth with 12-mm irradiation distance in study 2 but 1.1 mm in study 3 (microhardness measurements) is presumably caused by the scrape test being a rather inaccurate method.

In study 3 we found a slight drop of microhardness with increasing depth of measurement until a certain point at which the hardness was pronouncedly reduced (Fig. 5). This is in good accordance with previous studies by Ruyter & Øysæd (9) and by Yearn (11).

Watts et al. (10) have suggested that one should use the depth at which a 20% reduction in maximum hardness has occurred as a realistic measure of cure depth. On that basis, the results of study 3 were as follows: 0 mm irradiation distance = 3–3.5 mm sufficiently cured resin, 6 mm irradiation distance = 2.5–3 mm, and 12 mm irradiation distance = 2–2.5 mm; that is, even with 12 mm between the exit window and the surface of the resin the depth of cure was only reduced by 1 mm.

It should be kept in mind that the shades tested in the present study were the universal ones. Several authors have found that the more pigmented pastes, especially the brown shades, are the least curable (10, 12, 13). A curing depth of 2–2.5 mm with an irradiation distance of 12 mm can therefore not be obtained if one uses the darker pastes. In these cases one should use thinner layers.

It may be concluded that the depth of cure of light-activated composites does not follow a law of inverse squares but decreases in a moderate and linear manner with the distance between the exit window and the surface of the material. This finding implies that restorative resins, even in deep proximal cavities, may be sufficiently cured if one uses the standard procedures—that is, an effective lamp, thin layers, and, if necessary, prolonged curing time.

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