Shear Bond Strength with Increasing Light-Guide Distance from Dentin

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ABSTRACT

Background: In Class II composite restorations, the adhesive covering the gingival floor of the deep cavity preparation is 2 to 8 mm from the light guide and may not be adequately cured with a typical 10-second curing time.

Purpose: The purpose of this study was to evaluate the dentin bond strengths of resin composite when the curing light guide (quartz-tungsten-halogen light) was placed at various distances and to investigate the relationships between radiant exposure, degree of conversion, and shear bond strength.

Materials and Methods: Single Bond (3M ESPE, St. Paul, MN, USA) was placed onto the dentin following the manufacturer's directions. Four groups of 10 teeth were cured for 20 seconds through a 0, 2.3, 4.6, or 6.9 mm spacer. Two other groups of 10 teeth were cured through a 4.6 mm spacer for 40 seconds and 60 seconds, respectively. Z100 resin composite (3M ESPE) was placed over the cured adhesive and polymerized at the same distance as the adhesive. After 24 hours of storage in water, the shear bond strengths were tested. The irradiance through each spacer was measured using a digital radiometer. The degree of conversion of the adhesive was determined by near infrared spectroscopy. The data were analyzed using analysis of variance and Tukey-B post hoc tests.

Results: Dentin shear bond strengths decreased significantly with increasing distance, but they increased significantly when the curing time increased from 20 to 40 or 60 seconds. There is a linear correlation between shear bond strength, degree of conversion, and logarithm (radiant exposure).

Conclusion: Increasing curing time can compensate for the decreased bond strength owing to a decreased irradiance associated with increased curing distance.

CLINICAL SIGNIFICANCE

Under the conditions of this study, when curing the adhesives in deep proximal boxes with a quartz-tungsten-halogen light, the curing time should be increased to 40 to 60 seconds to ensure optimal polymerization.

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Postoperative sensitivity and poor marginal integrity in Class II resin composite restorations with deep proximal boxes are frequent reasons for restoration replacement. Since resin composite shrinks during polymerization, this sensitivity may be traced to marginal opening and poor seal, especially when the gingival margin is on dentin or cementum.[1] The bond to dentin and cementum is less predictable than the bond to enamel, and gingival leakage is significantly greater than leakage at occlusal enamel margins.[2–4]

There may be multiple reasons for the increased leakage at the gingival margin of Class II resin composite restorations: technique sensitivity of some dentin bonding systems,[5] contamination of the tooth surface during the application of the adhesive,[6] shrinkage of the resin composite,[7] composite placement method,[8] and poor polymerization of the adhesive and resin composite.[9,10] Inadequate polymerization of resin composite and adhesive may be due to poor output from an old curing light or the distance of the light guide from the bonding surface.[11–13]

The effects of the curing-light intensity on the degree of polymerization conversion of dental composites and their mechanical properties (e.g., hardness) have been studied extensively.[12–17] A logarithmic relationship between the hardness of dental composites and radiant exposure (energy density) received has been reported.[16,17] However, studies on the effect of the curing-light intensity on bonding strengths are rare.[18]

In this article more appropriate terminology is used according to the presentations at the 2004 Portland Composite Symposium (Portland, OR, USA).[19] For example, "irradiance" (in milliwatts per square centimeter) is used instead of "power density" to represent the light intensity or power per unit area; and "radiant exposure" is used instead of "energy density" to represent the total energy received per unit area, since "density" should be per unit volume (joules per cubic centimeter).

Near infrared (NIR) spectroscopy (11,000 to 5,500 cm^{-1}) is a convenient tool to measure the degree of polymerization conversion. This technique has been used to study the degree of conversion (DC) of different dental composites under various polymerization conditions.[20, 21] It uses the overture of absorption peak of vinyl C=C bonds around 6,168 cm^{-1}. Compared with mid-IR (4,000 to 400 cm^{-1}) spectroscopy, NIR spectroscopy has advantages of simple sample preparation, easy measurement (through glass slides), less sensitivity to moisture interference, and more accurate determination of baseline.

The purpose of this investigation was to examine the effects of curing with reduced light intensity on shear bond strength of resin composite to dentin by increasing the distance from the curing tip to the adhesive. The degree of polymerization conversion of the adhesive has been measured by NIR spectroscopy. The relationships between radiant exposure, DC, and shear bond strength have also been studied. The null hypothesis is that the distance from the curing tip to the adhesive has no effect on the bond strength.

MATERIALS AND METHODS

Shear Bond Strength Test

The materials and equipment used in this study are listed in Table 1. The dentin of 60 recently extracted, noncarious molar teeth was exposed to establish a bonding surface in superficial dentin by grinding the teeth on a model trimmer and finishing them with a series of SiC sandpaper, ending with 600-grit paper. An adhesive polytetrafluoroethylene (PTFE) tape (0.24 mm thick) with a 2.66 mm diameter hole was placed over the dentin to delineate the bonding area. The dentin was etched with 35% phosphoric acid etching gel for 15 seconds, rinsed, and air dried leaving the dentin moist, and two coats of Single Bond were placed onto the dentin. After air drying for 10 seconds, the Single Bond was cured for 20 seconds with an Optilux 500

TABLE 1. MATERIALS AND EQUIPMENT USED.	
Material or Equipment	**Manufacturer**
Z100 resin composite, batch no. 19971126	3M ESPE, St. Paul, MN, USA
Single Bond, lot no. 1917745	3M ESPE
Optilux 500 curing light	Demetron/Kerr, Danbury, CT, USA
Power Max 500 digital radiometer	Molectron Detector Inc., Portland, OR, USA
MTS 810 mechanical testing machine	MTS Systems, Minneapolis, MN, USA
Nicolet Nexus 670 FT-IR spectrometer	Thermo-Nicolet, Thermo Electron Co., Madison, WI, USA

curing unit. The output of this unit was verified (≥ 500 mW/cm^2) by the self-contained radiometer on the unit. Groups of 10 teeth were cured through a 5.5 mm opening of an acrylic plastic spacer that was placed between the dentin and the light guide to produce a space of 2.3 mm (one spacer), 4.6 mm (two spacers), or 6.9 mm (three spacers). For curing at 0 mm, the light guide tip was pressed directly onto the PTFE tape. Since the thickness of the Single Bond layer was smaller than that of the PTFE tape (0.24 mm), the light guide tip was at a negligible distance ("0 mm") from the adhesive but not in direct contact with the adhesive.

After curing the adhesive, a thin layer (< 0.5 mm) of Z100 resin composite (shade A-2) was placed over the adhesive and polymerized for 20 seconds at the same distance as the adhesive. A 6 mm long PTFE tube with a 4.5 mm inner diameter, partially filled (about 4 mm length) with Z100 composite, was applied over the cured composite surface and polymerized from the top and opposite longitudinal sides for 40 seconds each. The tube and PTFE tape were carefully removed, and the specimens were stored in water for 24 hours at room temperature. They were placed into an MTS mechanical testing machine (model 810), and a shear load was applied at the crosshead speed of 1 mm/m in until failure. The loads were converted to megapascals (MPa). Since declining bond strengths were observed with increasing distances, an additional two groups of specimens were made as outlined above, but the curing light was positioned at a fixed distance of 4.6 mm. Curing times for both the adhesive and the thin layer of composite in these two groups were 40 seconds and 60 seconds, respectively.

Irradiance Measurement

The irradiance of the Optilux 500 curing light at different distances was measured using a Power Max 500 digital radiometer, which gives slightly lower irradiance readings than the self-contained radiometer on the Optilux 500 unit. Its sensor area (20 mm diameter) is large enough to accommodate the acrylic plastic spacer (18 mm outer diameter). However, since its sensor area is larger than the curing light tip (10.8 mm diameter), if the curing tip is simply moved away for a short distance, it can still detect most of the light irradiation. To measure the irradiance accurately within a defined area, the three acrylic plastic spacers (each 2.3 mm thickness and a 5.5 mm diameter hole) were coated with black-marker ink on both sides. A polyester film matrix strip (0.04 mm thick, 10 mm wide) was also coated with the black-marker ink on both sides, clapped between a pair of acrylic plastic slides, and drilled together to form a 5.5 mm hole. This blackened polyester film strip with 5.5 mm hole served as the "0 mm spacer." The other areas of the Power Max sensor were also covered with an additional blackened polyester film strip. The irradiance was measured through a

5.5 mm hole at 0, 2.3, 4.6, and 6.9 mm distances. Since the irradiance readings changed during first few seconds and stabilized after 10 second, the irradiance was recorded at 10 and 20 seconds during each measurement. The measurement was repeated four times, and the average of eight readings was reported at each distance. The radiant exposure (in joules per square centimeter) was calculated by multiplying the irradiance (in milliwatts per square centimeter) with the curing time (in seconds) and divided by 1,000.

Degree of Conversion of the Adhesive

NIR spectroscopy was used to measure the degree of polymerization conversion of the adhesive that was light cured at different distances and times. A Nexus 670 FT-IR spectrometer was used throughout the experiment. A Smart NIR UpDRIFT, a top-loading diffuse reflection accessory (Thermo-Nicolet), was used to collect the NIR spectra. This device allows fast analysis of samples directly from glass or plastic containers. All spectra were recorded at wavenumber of 5,500 to 8,000 cm^{-1}, a resolution of 8 cm^{-1}, and a scan number 110. First, an adhesive PTFE tape (0.24 mm thick—the same as that used in shear bond strength test) with a 4.0 mm hole was pressed on a thin glass slide (22 × 22 mm, 0.17 mm thick). The glass slide was placed on top of the Smart NIR UpDRIFT with the PTFE tape hole at the center of the sampling window (6 mm diameter). Then the background was collected. After that, a small drop of the Single Bond adhesive monomer was brushed onto the glass slide, covering the PTFE tape hole but below the level of the PTFE tape. The adhesive was light cured at the various conditions described above. The NIR spectra were collected for each Single Bond monomer and light-cured adhesive. The NIR spectroscopy experiment was repeated three times under each light-cure condition. The DC was calculated using the ratio of the absorption peak area at 6,168 cm^{-1} from the light-cured adhesive and its monomer. The NIR spectrum of the PTFE tape was also collected, and no peaks were found in the measured wavenumber range.

Data Analysis

The data were analyzed using one-way analysis of variance and Tukey-B post hoc tests, with significance (α) set at .05. SPSS 11.0 software (SPSS Inc., Chicago, IL, USA) was used for data analysis, and MS Excel (Microsoft, Redmond, WA, USA) was used for linear regression and plots.

RESULTS

All experimental data are listed in Table 2. Figure 1 displays the shear bond strengths under different light-curing conditions. Dentin shear bond strengths (SBS) significantly decreased with each increase in distance ($p < .01$). Increasing cur-

TABLE 2. IRRADIANCES, RADIANT EXPOSURES, DCS, AND SHEAR BOND STRENGTHS AT DIFFERENT CURING DISTANCES AND TIMES.

Distance (mm)	Curing Time (s)	Irradiance (mW/cm^2)	Radiant Exposure (J/cm^2)	DC of Adhesive (%)	Shear Bond Strength (MPa)
0	20	458 ± 17	9.16 ± 0.34	84.53 ± 3.54	21.42 ± 0.05
2.3	20	264 ± 27	5.28 ± 0.54	79.11 ± 4.59	12.32 ± 0.47
4.6	20	169 ± 11	3.38 ± 0.22	68.73 ± 5.14	7.91 ± 0.36
6.9	20	121 ± 3	2.43 ± 0.05	65.35 ± 6.19	4.51 ± 0.29
4.6	40	169 ± 11	6.77 ± 0.44	76.45 ± 3.16	18.19 ± 0.19
4.6	60	169 ± 11	10.15 ± 0.66	83.11 ± 2.48	21.44 ± 0.20

DC = degree of conversion.

ing time to 40 seconds significantly increased the shear bond strength compared with those achieved with the 20-second cure, but it was still significantly less than the bond strength at 20 seconds when the curing distance was 0 mm. When the curing time was increased to 60 seconds, bond strength was not significantly different from that for the control.

Figure 2 shows the radiant exposure under different light-curing conditions. The radiant exposure decreased with increasing distance; however, increasing the curing time can compensate for the change of radiant exposure.

Figure 3 shows the NIR spectra of the Single Bond monomer and those cured for 20 seconds at different distances. The height and area of the peak at 6,168 cm^{-1} increased with increasing distance between the light guide tip and the adhesive. The DC was calculated using the following equation:

$$DC\ (\%) = (1 - A_p/A_m) \times 100$$

where A_p is the area of the cured adhesive (polymer) and A_m is the area of adhesive monomer.

Figure 4 shows the DC under different light-curing conditions. DCs with the same 20-second curing time decreased with increasing distance. The DCs at 4.6 and 6.9 mm were significantly lower than that of the control (at 0 mm) ($p < .05$). However, when curing time was increased to 40 or 60 seconds, the DCs at 4.6 mm increased and became statistically the same as that of control ($p > .05$).

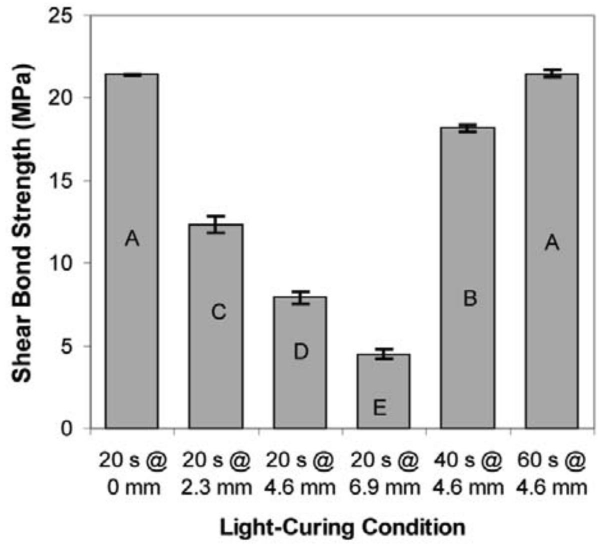

Figure 1. Shear bond strengths at different light-curing conditions. Different letters indicate significant differences.

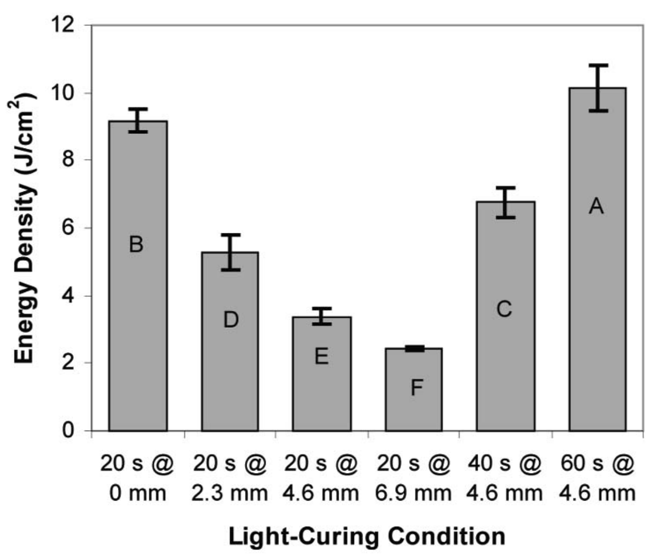

Figure 2. Radiant exposures at different light-curing conditions. Different letters indicate significant differences.

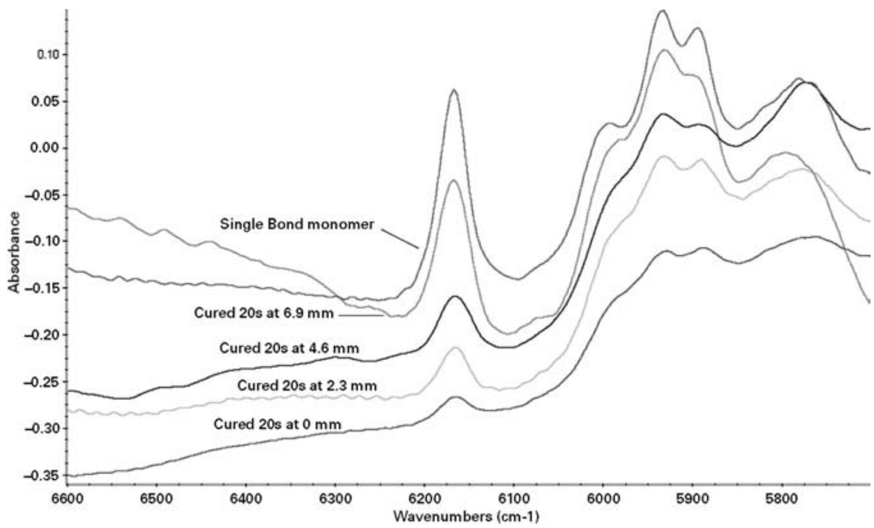

Figure 3. Near infrared spectra of Single Bond monomer and the adhesives cured for 20 seconds at different distances.

Linear relationships were found when the DCs and shear bond strengths were plotted against the logarithm of radiant exposure (E). Figure 5 shows a linear relationship between DC and Log(E) ($R^2 = .9226$). Figure 6 shows a linear relationship between shear bond strength and Log(E) ($R^2 = .9809$).

DISCUSSION

Small, 2 mm diameter light guides allow the curing tip to be positioned close to the gingival margin. However, conventional light tips with large diameters have limited access to the gingival margin and deep proximal boxes. Therefore, there is a space between the tip of the light guide and the surface being cured. The initial results of this study demonstrated that bond strength decreases as the distance between the curing light and the curing surface increases (see Figure 1). This has important clinical significance for preparations with deep proximal boxes, especially when the margins may be on the cementum and dentin. Several in vitro studies have shown that light intensity decreases as the distance from the curing tip to composite increases.[10,12,13] Other studies have shown that when composites are placed in preparations with margins in dentin/cementum, leakage occurs.[4,5] It is possible that the decreased bond strength produced with poor polymerization of the adhesive contributed to the increased microleakage seen in these studies. When gingival margins are placed apical to the cementoenamel junction, polymerization shrinkage can produce gaps at the restorative interface.[1,6,13] Clinically, when the gingival margin of a Class II preparation is placed apical to the cementoenamel junction, the chances are good that this margin will be subgingival. Hemorrhage from the adjacent gingiva can lead to contamination and marginal bond failure.[6] These factors reduce bond strength at the critical gingival marginal area.

In this current study, it was found that increasing the curing time could compensate for the loss of bond strength owing to the increased curing distance. For example, increasing the curing time to 60 seconds at 4.6 mm produced the same shear bond strength statistically ($p > .05$) as that of the control (curing 20 s at 0 mm).

To further understand the influence of light-curing conditions on the polymerization process and bond strength, the irradiance (and thus the radiant exposure) and the degree of polymerization conversion were measured under different light-curing conditions. It was found that the radiant exposure and DC changed with the light-curing conditions in a pattern similar to that of shear bond strength; that is, they decreased with increasing distance but increased with increasing curing time (see Figures 1, 2, and 4). When the DCs and shear bond strengths were plotted against the logarithm of radiant exposure, linear relationships were found between DC and Log(E) (R^2= .9226; see Figure 5) and between shear bond strength and Log(E) (R^2= .9809, Figure 6). Similar logarithmic relationships between the hardness of dental composites and radiant exposure (energy density) received have been reported.[16,17] An exponential relationship has also been reported between the DC and the radiant exposure (energy density).[22] Therefore, the findings in this study are consistent with those of previous reports on dental composites.

This study has provided strong evidence that increasing the distance between the tip of curing light and the adhesive causes a decrease in radiant exposure (owing to divergence of the curing light), which leads to a decrease of degree of polymerization conversion, which in turn produces lower bond strengths. When curing adhesive in deep (proximal) boxes, the conventional 10-second curing time is insufficient. It should be increased to 40 to 60 seconds to compensate for the decreased bond strength owing to loss of radiant exposure. This applies to the initial increment of the composite as well as the adhesive layer.

Another interesting finding in this study is that when the radiant exposure decreased by 73% (from 9.16 to 2.43 J/cm^2), the DC decreased by only 27% (from 84.53 to 65.35%), whereas the shear bond strength decreased by nearly 80% (from 21.42 to 4.51 MPa) (see Table 2). We believe that even a small change of degree of polymerization conversion of the adhesive (and possibly the first thin layer of composite) has a strong influence on the mechanical properties and durability of the (tooth-adhesive and adhesive-composite) interfaces in the wet (oral) environment. A lower DC means that a significant amount of adhesive and composite monomers can leach out in water, dentinal fluid, and saliva. It is spec-

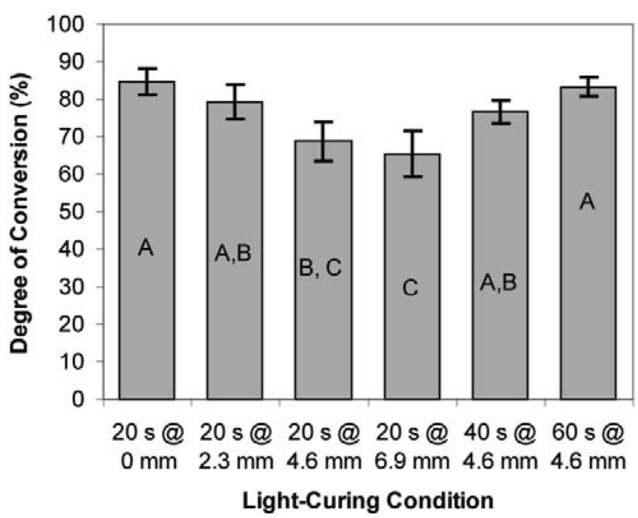

Figure 4. Degrees of conversion of the adhesive at different light-curing conditions. The same letters on groups indicate that there was no significant difference between them.

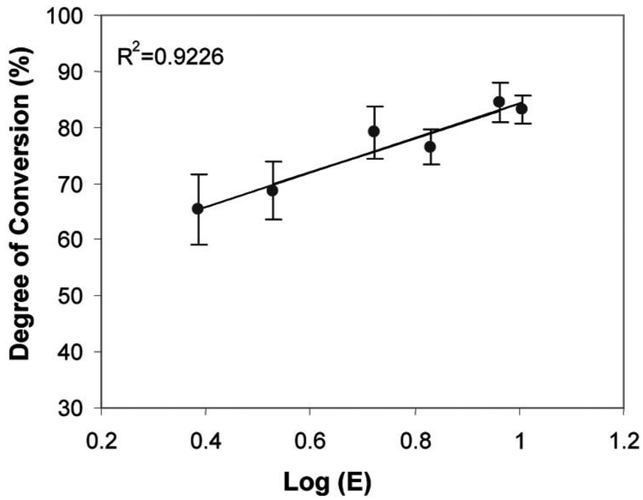

Figure 5. Correlation between the degree of conversion of the adhesive and the logarithm of radiant exposure (E).

ulated that the leaching of uncured monomers may result in porosity in the adhesive layer. Also the dentinal fluid and saliva may diffuse into the porous adhesive layer to increase staining and accelerate the deterioration of the adhesive interface. The combination of these effects can lead to microleakage when the restoration is subject to the stress caused by polymerization shrinkage or thermal expansion/contraction of the resin composite. The relationship between DC and the porosity, staining, and microleakage of the adhesive layer needs to be investigated in future research. It is vital to cure the adhesive and

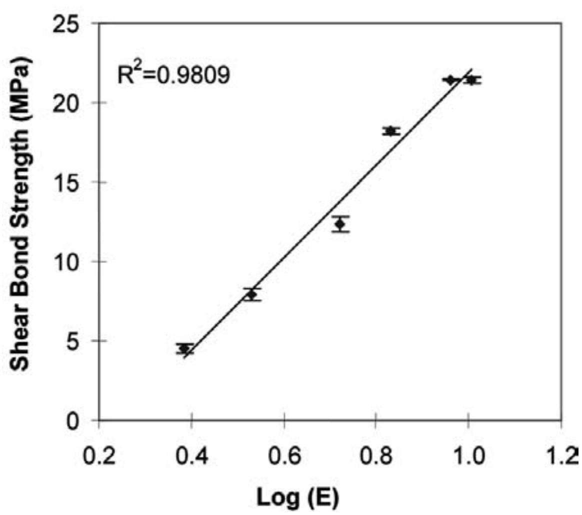

Figure 6. Correlation between the shear bond strength and the logarithm of radiant exposure (E).

the first layer of composite adequately to ensure the long-term performance of the restoration. Any loss of radiant exposure caused by increased distance should be compensated for by increasing the curing time.

CONCLUSIONS

The following conclusions can be drawn from this study:

- Shear bond strength decreases significantly as the distance from the curing light tip to the adhesive increases ($p < .05$). Therefore, the null hypothesis has been rejected.
- Increasing the curing time can compensate for the decreased shear bond strength owing to the decreased irradiance associated with an increased curing distance.
- Cure time should be increased when curing deep proximal boxes coated with adhesive. A cure time of 40 to 60 seconds is recommended when the gingival floor of a Class II cavity preparation is 6 to 7 mm below the occlusal floor.

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REFERENCES

1. Lui JL, Shigeyuki M, Setros JC, et al. Margin quality and microleakage of Class II composite resin restorations. J Am Dent Assoc 1987;114:49–54.
2. Hilton TJ, Schwartz RS, Ferracane JL. Microleakage of four Class II resin composite insertion techniques at intraoral temperature. Quintessence Int 1997;28:135–44.
3. Lundin SA, Noren JG. Marginal leakage in occlusally loaded, etched Class II composite resin restorations. Acta Odontol Scand 1991;49:247–54.
4. Thonemann B, Fenderlin M, Schmalz G, Grundler W. Total bonding vs. selective bonding: marginal adaptation of Class II composite restorations. Oper Dent 1999;24:261–71.
5. Hilton TJ. Can modern restorative procedures and materials reliably seal cavities? In vitro investigations. Am J Dent 2002; 15:198–210 (Part 1), 279–81 (Part 2).
6. Gallo JR, Burgess JO, Xu X. Composite resin to dentin bond strength with contamination [abstract]. J Dent Res 1998;77:238.
7. Davidson CL, Feilzer AJ. Polymerization shrinkage and polymerization shrinkage stress in polymer based restoratives. J Dent 1997;25:435–40.
8. Ciucchi B, Bouillaguet S. Delaloye M, Holz J. Volume of internal gap formed under composite restorations in vitro. J Dent 1997;25:305–12.
9. Hinoura K, Miyazaki M, Onose H. Effect of irradiation time to light-cured resin composite on dentin bond strength. Am J Dent 1991;4:273–6.
10. Rueggeberg FA, Jordan D. Light tip distance and cure of resin composite [abstract]. J Dent Res 1992;71:188.
11. Pilo R, Oelgresser D, Cardash HS. A survey of output intensity and potential depth of cure among light-curing units in clinical use. J Dent 1999;27:235–41.
12. Pires JA, Cvitko E, Denehy GE, Swift EJ. Effects of curing tip distance on light intensity and composite resin microhardness. Quintessence Int 1993;24:517–21.
13. McCabe JF, Carrick TE. Output from visible-light activated units and depth of cure of light-activated composites. J Dent Res 1989;68:1534–49.
14. Miyazaki M, Hattori T, Ichiishi Y, et al. Evaluation of curing units used in private dental offices. Oper Dent 1998;23:50–4.
15. Sakaguchi RL, Douglas WH, Peters MC. Curing light performance and polymerization of composite restorative materials. J Dent 1992;20:183–8.
16. Davidson CL, de Gee AJ. Light-curing units, polymerization, and clinic implications. J Adhes Dent 2000;2:167–73.
17. Price RBT, Felix CA, Andreou P. Effects of resin composite composition and irradiation distance on the performance of curing lights. Biomaterials 2004;25:4465–77.
18. Miyazaki M, Hinoura K, Onose H, Moore BK. Influence of light intensity on shear bond strength to dentin. Am J Dent 1995;8:245–8.
19. Kirkpatrick SJ. A primer on radiometry. Dent Mater 2005;21:21–6.
20. Stansbury JW, Dickens SH. Determination of double bond conversion in dental resins by near infrared spectroscopy. Dent Mater 2001;17:71–9.
21. Trujillo M, Newman SM, Stansbury JW. Use of near-IR to monitor the influence of external heating on dental composite photopolymerization. Dent Mater 2004;20:766–77.
22. Halvorson RH, Erickson RL, Davison CL. Energy dependent polymerization of resin-based composite. Dent Mater 2001;13: 121–30.

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