©Operative Dentistry, 2020, **45-3,** E141-E155

Effect of Curing Light and Exposure Time on the Polymerization of Bulk-Fill Resin-Based Composites in Molar Teeth

CAK Shimokawa • ML Turbino • M Giannini • RR Braga • RB Price

Clinical Relevance

Light curing a molar bulk-fill mesio-occluso-distal restoration from a single position at the center of the occlusal surface may result in inadequate photopolymerization of the resin-based composite at the bottom of the proximal boxes.

SUMMARY

Objectives: This study examined the influence of different light-curing units (LCUs) and exposure times on the microhardness across bulk-fill resin-based composite (RBC) restorations in a molar tooth.

Methods and Materials: Tip diameter, radiant power, radiant exitance, emission spectra, and light beam profile were measured on two single-emission-peak LCUs (Celalux 3 and DeepCure-S) and two multiple-peak LCUs (Bluephase 20i and Valo Grand). A mold was made using a human molar that had a 12-mm mesial-distal length, a 2.5-mm deep occlusal box, and two 4.5-mm deep proximal boxes. Two bulk-fill RBCs (Filtek Bulk Fill Posterior and Tetric EvoCeram Bulk Fill) were photoactivated for 10 seconds and for 20 seconds, with the light guide positioned at the center of the occlusal surface. Microhardness was then measured across the transverse surface of the restorations. The light that reached the bottom of the proximal boxes was examined. Data were statistically analyzed with the Student *t*-test, two-way analysis of variance, and the Tukey *post hoc* test (α=0.05).

Results: The four LCUs were different regarding all the tested characteristics. Even when using LCUs with wide tips and a homogeneous beam profile, there were significant differences in the microhardness results obtained at the

*Carlos Alberto Kenji Shimokawa, postdoctoral researcher, Restorative Dentistry, School of Dentistry, University of São Paulo, São Paulo, Brazil

Míriam Lacalle Turbino, full professor, Restorative Dentistry, School of Dentistry, University of São Paulo, São Paulo, Brazil

Marcelo Giannini, associate professor, Restorative Dentistry, Piracicaba Dental School, State University of Campinas, Piracicaba, Brazil

Roberto Ruggiero Braga, full professor, Biomaterials and Oral Biology, School of Dentistry, University of São Paulo, São Paulo, Brazil

Richard Bengt Price, professor, Dental Clinical Sciences, Faculty of Dentistry, Dalhousie University, Halifax, Nova Scotia, Canada

*Corresponding author: Avenida Professor Lineu Prestes, 2227, São Paulo, São Paulo 05508-000, Brazil; e-mail: carlos.shimokawa@usp.br

https://doi.org/10.2341/19-126-L

central and proximal regions of the RBCs (p<0.05). LCUs with wider tips used for 20 seconds produced higher microhardness values (p<0.05). The multiple-peak LCUs produced greater hardness values in Tetric EvoCeram Bulk Fill than did the single-emission-peak LCUs (Celalux 3 and DeepCure-S). Results for the light measured at the bottom of proximal boxes showed that little light reached these regions when the light tip was positioned at the center of restorations.

Conclusions: Curing lights with wide tips, homogeneous light beam profiles, and longer exposure times are preferred when light-curing large MOD restorations. Light curing from more than one position may be required for adequate photopolymerization.

INTRODUCTION

The manufacturers of light-cured bulk-fill resin-based composites (RBCs) advocate that their RBCs can be adequately light-cured in just one increment that may be up to 5 mm thick, thus saving time and potentially reducing defects and porosity within the bulk of the restoration. Consequently, bulk-fill RBCs have gained in popularity, and some studies have already reported that bulk-fill RBCs have both adequate depth of cure and mechanical properties.[1-5] Satisfactory clinical performance has been reported after six years when each 4-mm-thick increment of one brand of flowable bulk filled composite was light-cured for 20 seconds, and the occlusal parts of Class I and II restorations were covered with a conventional resin composite material.[6] However, bulk curing from just one position may be inadequate when extensive restorations are photoactivated using a small light tip because some regions of the restorations that are not covered by the light tip may show reduced polymerization.

There are many light-curing units (LCUs) available for dentists to use. These LCUs have different tip diameters, they deliver different radiant powers, radiant exitance, emission spectra, and have different light beam profiles.[7-9] Even if the LCU tip covers the entire restoration, the resin polymerization may be adversely affected if the light is not uniformly emitted across the light tip, since some regions of the restoration may receive insufficient light and some regions may receive very high irradiance values.[10,11] Thus, the light-curing of extensive bulk-fill RBC restorations in molar teeth from just one position should be evaluated.

The exposure time is a critical factor that influences the polymerization of RBC restorations.[12] Longer exposure times should improve the polymerization and ultimately reduce the effects of any light beam inhomogeneity. Different RBCs are also available, and factors regarding their composition, shade, thickness, and translucency can all influence their interaction with the light from the LCU.[13] Also, depending on the photoinitiators that are present within the RBCs, the photopolymerization of the RBC will be affected by the emission spectra from the LCU.[14,15]

The mold used when fabricating the specimens for *in vitro* tests has a substantial effect on the polymerization of RBCs.[16,17] The International Organization for Standardization (ISO) has an international standard for testing depth of cure of dental polymer-based materials, but this standard uses a 4-mm-diameter metal mold that does not reproduce how bulk-fill RBCs are used clinically.[18] Ideally, a mold that closely simulates clinical situations should be used, but there exists a significant heterogeneity regarding different methods used to test the depth of cure of bulk-fill RBCs.[4]

The aim of this study was to examine the influence of the tip diameter, radiant power, radiant exitance, emission spectrum, light beam profile, and two different exposure times (10 and 20 seconds) from four different LCUs on the curing profile of mesio-occluso-distal (MOD) restorations made from two different bulk-fill RBCs light-cured in a human molar tooth. The null hypotheses of this study were the following:

1) The characteristics of the LCUs will not influence the curing profile of the bulk-fill RBC restorations.
2) A longer exposure time will not influence the curing profile of bulk-fill RBC restorations.

In addition, the effect of light guide position on the light reaching the bottom of the proximal boxes was assessed.

METHODS AND MATERIALS

Four light-emitting-diode (LED) LCUs from major manufacturers were used: Bluephase 20i (Ivoclar Vivadent, Schaan, Liechtenstein), Celalux 3 (VOCO, Cuxhaven, Germany), Elipar DeepCure-S (3M Oral Care, St Paul, MN, USA), and Valo Grand (Ultradent Products Inc, South Jordan, UT, USA) (Table 1). These LCUs were used to photoactivate two bulk-fill RBCs: one that uses only camphorquinone (CQ)

Table 1: *Light-Curing units, measured external tip diameter (mm), measured effective tip diameter (mm), mean ± standard deviation of the radiant power results (mW), mean ± standard deviation of the calculated radiant exitance results (mW/cm²), and mean ± standard deviation of the calculated radiant exposure results (J/cm²) for a 10-second exposure (mean ± standard deviation of calculated radiant exposure results for a 20-second exposure (J/cm²) also reported;* n = *5 repeats made for radiant power measurements)*

Light-Curing Unit (Serial Number)	External Tip Diameter (mm)	Effective Tip Diameter (mm)	Mean Radiant Power (mW)	Mean Radiant Exitance (mW/cm²)	Mean Radiant Exposure, 10 s (J/cm²)	Mean Radiant Exposure, 20 s (J/cm²)
Bluephase 20i (P626170S548780)	8.0	7.2	570.0 ± 2.7	1399.9 ± 6.6	14.0 ± 0.1	28.0 ± 0.1
Celalux 3 (1637091)	8.0	7.1	432.4 ± 4.4	1092.1 ± 11.2	10.9 ± 0.1	21.8 ± 0.2
Elipar DeepCure-S (933112-001111)	9.8	9.0	792.9 ± 4.5	1246.3 ± 7.1	12.5 ± 0.1	24.9 ± 0.1
Valo Grand (MFG3277-5)	15.0	11.6	1007.6 ± 13.0	953.4 ± 12.2	9.5 ± 0.1	19.1 ± 0.2

as photoinitiator (Filtek Bulk Fill Posterior Restorative, shade A2, 3M Oral Care) and one that contains CQ plus an additional photoinitiator (Ivocerin)[14] (Tetric EvoCeram Bulk Fill, shade IVA, Ivoclar Vivadent).

Characterization of the LCUs

The tip diameter, radiant power, radiant exitance, emission spectrum, and light beam profile of the LCUs were examined, as previously described.[19] In summary, the effective internal tip diameter from where the light was emitted was measured with a digital caliper (Mitutoyo, Kawasaki, Japan). The radiant power and the emission spectra of the LCUs were measured with a six-inch integrating sphere (Labsphere, North Sutton, NH, USA) coupled to a fiber-optic spectrometer USB-4000 (Ocean Optics, Dunedin, IL, USA) with the tip 2-mm away from the entrance of the sphere (n=5 measurements). The radiant exitance was calculated as the quotient of the radiant power and the effective tip area. The light beam profile of the LCUs was assessed with a Laser Beam Profiler (Ophir Spiricon, Logan, UT, USA), at a 2-mm distance from a 40-degree holographic screen. The two-dimension (2D) Flatness Top-Hat results for the four LCUs were calculated by the BeamGage software (Ophir Spiricon) according to the formula $Fn_{(Z)} = E_n/E_{max}$, where E_n is the effective average power of the light beam and E_{max} is the peak power in the light beam.[20] The threshold power/energy density was set to a value of 0 to ensure that all of the light emitted by the LCU was used in the Top-Hat calculations. Data were exported to OriginPro 2017 software (OriginLab, Northampton, MA, USA) to produce scaled images of the light that reached the top surface of the RBC specimens when the LCU tip was 2-mm away from the RBC. The distribution of the light across its tip surface was examined both with and without a 400 ± 5-nm narrow bandpass filter (#65-132, Edmund Industrial Optics, Barrington, NJ, USA) to verify the distribution of just the violet portion of the light (~400 nm) across the tip compared to all of the light from the LCU.

Tooth Mold and Specimen Preparation

After receiving Dalhousie University research ethics board approval to collect and use human teeth (#2015-3632), a human mandibular first molar that was 12-mm in mesio-distal length was used to make the mold for the specimens (Figure 1). The tooth cusps were ground flat, and the tooth was embedded in autocuring acrylic resin. Then, the tooth was cut into three slices in the mesio-distal direction. The central slice was 2-mm wide in the bucco-lingual direction and had the acrylic resin removed up to the cemento-enamel junction to expose the clinical crown. An impression of the external contour of the tooth at the central slice was taken with vinyl polysiloxane (VPS) Extrude XP Heavy Body (Kerr Corp, Orange, CA, USA) that was used later as a guide so that all the specimens would be made to the same external contour (Figure 1a). The central tooth slice received a MOD preparation that was 12-mm mesio-distal width, 2-mm bucco-lingual width, 2.5-mm occlusal box depth, and 4.5-mm proximal box depth (Figure 1b). Then, the three slices were clamped together with a 0.14-mm-thick microscope cover glass (Globe Scientific Inc, Paramus, NJ, USA) between each slice. The mold was then filled with the RBCs, and a jig was used to place the specimens in the same position under the tip of the LCU. The RBC was then photoactivated for either 10 or 20 seconds with the LCU fixed with the tip positioned at the center of the restoration and 2-mm away from the top surface of the RBC (Figure 1c). After photoactivation, specimens were removed from the mold, the cover glass slips were removed, and the specimens were stored in the dark for 24 hours in air at 37°C before hardness testing.

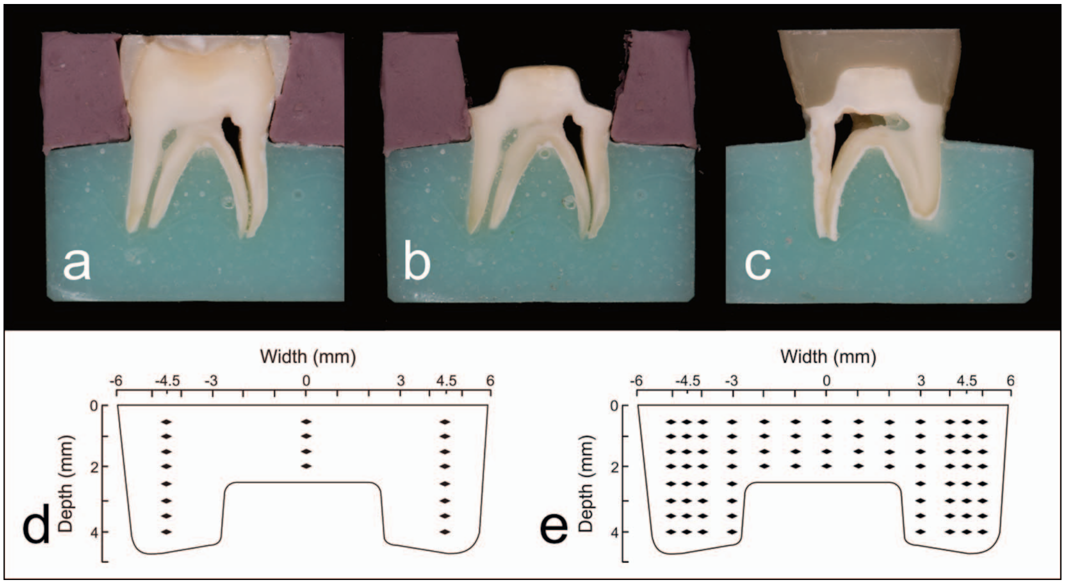


Figure 1. *Molar human tooth mold and indentation scheme. (a): Impression taken with vinyl polysiloxane to guide the anatomical contour of the restorations. (b): MOD preparation with the guide in position. (c): Restoration made using the mold. (d): Indentation scheme used for the low-resolution hardness maps. (e): Indentation scheme used for the high-resolution hardness maps.*

Microhardness Measurements

The Knoop microhardness of the transverse surface of the specimens was measured every 0.5 mm in depth at three positions: center, mesial, and distal (4.5 mm away from the center) for a total of 20 indents per specimen (four at the center and eight at each proximal position; Figure 1d). To avoid damaging the specimens, a load of 15 gf was applied for eight seconds (HMV123 microhardness tester, Mitutoyo). In addition, high-resolution microhardness maps were produced using the indentation scheme shown in Figure 1e (where a total of 84 indents were made per specimen). Two specimens for each RBC and LCU were used for that purpose, and the results were averaged. One transverse surface of the central slice was analyzed per specimen, and this surface was standardized.

Light Transmission Through the Specimen

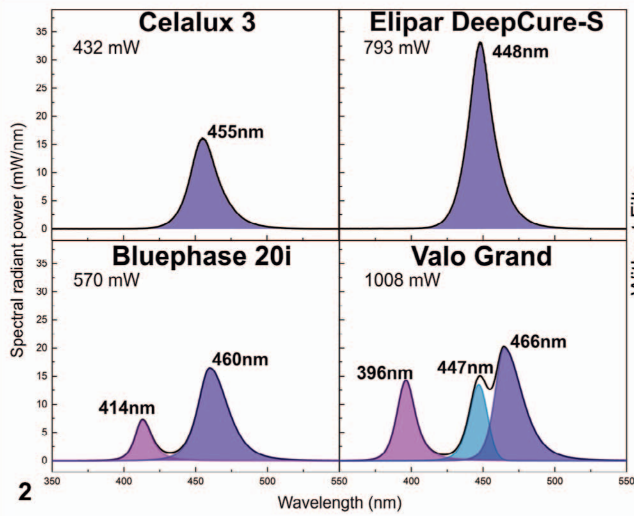
To evaluate the light transmitted through the RBC to the bottom of the proximal boxes, a second mold was made using another human molar. The tooth had its cusps ground flat, and a MOD restoration was made in this tooth. The tooth was then embedded in opaque acrylic resin up to the restoration surface, and its cervical region was ground away to reach the bottom of the proximal boxes of each resin restoration. The specimen was then positioned in the beam profiler to measure the light that reached down through the RBC to the bottom of the proximal boxes when the light tip was 2 mm away from the surface in three positions over the restoration (center, mesial, and distal).

Statistical Analysis

The Kolmogorov-Smirnov test was applied to verify the normal distribution of hardness data. Then, two-way repeated measures analysis of variance and Tukey *post hoc* tests were used (α=0.05). The two different RBCs and exposure times were analyzed separately. Also, means of the shallower depths (0.5, 1.0, 1.5, and 2.0 mm) were used to compare the central region and both proximal boxes of the RBC. The Student *t*-test was used to compare the effects of the two exposure times (α=0.05). Light transmission through the specimens was visually analyzed but was not subjected to statistical analysis.

RESULTS

The characterization results of the four LCUs are shown in Table 1. The LCUs varied regarding their effective tip diameters: The Valo Grand had the widest tip (Ø 11.6 mm, area 105.7 mm^2), and Celalux 3 had the narrowest tip (Ø 7.1 mm, area 39.6 mm^2). The Valo Grand delivered the lowest radiant exitance (953 mW/cm^2), and Bluephase 20i delivered the highest radiant exitance (1400 mW/cm^2). The Celalux 3 and Elipar DeepCure-S delivered an emission spectrum that had a single peak, while Bluephase 20i and Valo Grand delivered an emission spectrum with multiple wavelength peaks (Figure 2). Regarding the light beam profile, Celalux 3



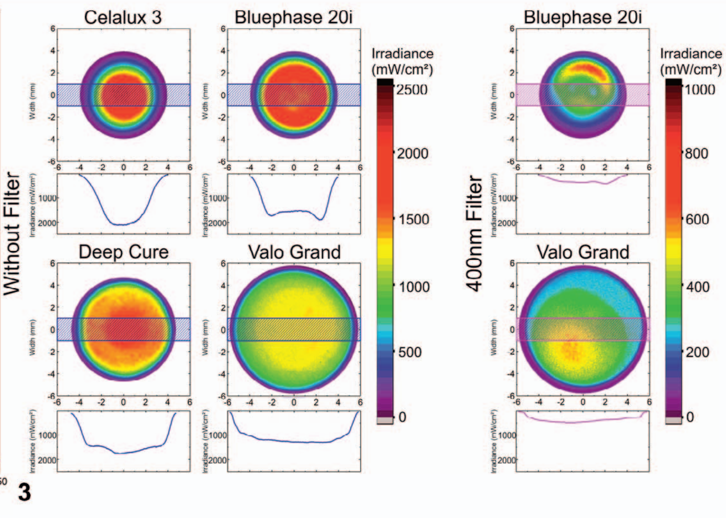


Figure 2. *Emission spectrum of the light-curing units. Violet areas (below 425 nm) represent the wavelengths of violet light, while blue areas (above 425 nm) represent the wavelengths of blue light.*

Figure 3. *Light beam profile of the light-curing units measured at a 2-mm distance from the screen. The beam profile of the light that adequately covered the restorations was evaluated without filter (blue lines) and with a 400-nm filter (violet lines on the right side) to show the violet light only.*

delivered an inhomogeneous beam, with most of the radiant exitance concentrated in a 4-mm region at the center of the light tip, while Valo Grand delivered a more homogeneous beam profile that was evenly distributed across the 11.6-mm tip (Figure 3). The Flatness Top-Hat results of the light beam from each LCU from worst to best were: Celalux 3: 0.380; Bluephase 20i: 0.547; Elipar Deep-Cure-S: 0.600; and Valo Grand: 0.675.

Tables 2 and 3 show that even when using LCUs that had wide tips and homogeneous beam profiles, such as Deep Cure and Valo Grand, there was a difference between the microhardness values measured in the first 2 mm of the occlusal and the proximal boxes of the restorations ($p<0.05$). The microhardness maps also illustrate these differences, with the center of the specimen displaying more red or yellow color (higher hardness), while the proximal boxes had more green or blue colors, indicating lower hardness values (Figure 4).

The use of an increased exposure time (20 seconds) always produced greater hardness values ($p<0.05$) for both RBCs. As the exposure time increased, the hardness maps became more uniform, as illustrated by the improved color uniformity (Figure 4). Table 4 shows that, overall, when photoactivated for 10 seconds with the different LCUs positioned at the center of the restorations, the Filtek Bulk Fill Posterior specimens were not significantly different ($p\geq0.05$). When the exposure time was increased to 20 seconds, the Deep Cure and Valo Grand LCUs that both had wider tips, produced greater hardness values (Table 5).

When using the 10-second exposure time, the Valo Grand produced the highest hardness values ($p<0.05$) on the specimens of Tetric EvoCeram Bulk

Table 2: *Overall Means ± Standard Deviations of the Knoop microhardness values to a depth of 2 mm, measured in the central, mesial (4.5 mm from the center), and distal (4.5 mm from the center) regions of the specimens made with Filtek Bulk Fill Posterior (each exposure time analyzed separately)[a]*

Light-Curing Unit	**10-s Exposure**			**20-s Exposure**		
	Mesial	**Central**	**Distal**	**Mesial**	**Central**	**Distal**
Bluephase 20i	42.3 ± 3.3 Bb	53.2 ± 0.1 Aa	31.1 ± 1.9 Cc	46.6 ± 0.2 Bb	54.0 ± 0.4 Ba	45.0 ± 0.2 Bc
Celalux 3	37.3 ± 1.5 Cb	52.0 ± 1.8 Aa	30.6 ± 1.6 Cc	46.6 ± 0.2 Bb	54.3 ± 0.3 Ba	45.5 ± 0.4 Bb
DeepCure-S	48.0 ± 1.4 Ab	54.1 ± 1.0 Aa	39.6 ± 1.4 Bc	53.3 ± 0.6 Ab	56.5 ± 0.5 Aa	50.8 ± 0.2 Ac
Valo Grand	48.6 ± 0.8 Ab	52.4 ± 1.6 Aa	44.3 ± 2.0 Ac	54.0 ± 0.5 Ab	57.3 ± 0.4 Aa	52.1 ± 0.6 Ac

[a] *Different uppercase letters indicate statistical differences within columns (light curing units); different lowercase letters indicate statistical differences within rows ($p<0.05$). N = 5 repeats.*

Table 3: *Overall Means ± Standard Deviations of the Knoop Microhardness Values to a depth of 2 mm, measured in the central, mesial (4.5 mm from the center), and distal (4.5 mm from the center) regions of the specimens made with Tetric Evoceram Bulk Fill (each exposure time analyzed separately)*[a]

Light-Curing Unit	10-s Exposure			20-s Exposure		
	Mesial	Central	Distal	Mesial	Central	Distal
Bluephase 20i	32.4 ± 1.6 Bb	42.5 ± 0.9 Ba	26.7 ± 2.2 Bc	34.2 ± 1.5 Cb	45.5 ± 0.5 Ba	32.5 ± 1.6 Cc
Celalux 3	24.7 ± 1.7 Cb	38.8 ± 1.2 Ca	20.4 ± 1.2 Cc	31.7 ± 1.0 Db	40.2 ± 0.6 Ca	30.6 ± 0.6 Db
DeepCure-S	33.0 ± 0.5 Bb	39.1 ± 0.8 Ca	27.5 ± 0.6 Bc	40.3 ± 0.8 Bb	44.4 ± 0.7 Ba	36.6 ± 1.2 Bc
Valo Grand	40.9 ± 1.3 Ab	45.9 ± 1.7 Aa	36.9 ± 1.9 Ac	45.5 ± 0.5 Ab	49.8 ± 0.7 Aa	45.6 ± 1.1 Ab

[a] *Different uppercase letters indicate statistical differences within columns (light curing units); different lowercase letters indicate statistical differences within rows ($p<0.05$). N = 5 repeats.*

Fill followed by the Bluephase 20i, and no significant difference was found between Celalux 3 and Deep Cure-S (Table 6). When the exposure time was increased to 20 seconds, the Valo Grand still produced the highest hardness results, followed by Deep Cure, Bluephase 20i, and Celalux 3. At the 1.5- and 2.0-mm depths, the specimens photocured using Valo Grand reached the highest hardness values, and there was no difference between the Bluephase 20i and Deep Cure. The Celalux 3 produced the lowest Knoop hardness values (Table 7).

The light transmission results show that even when the wide tip diameter of the Valo Grand was placed at the center of the 12-mm wide restoration, very little light reached down to the bottom of the 4-mm deep proximal boxes. When the tip of the LCUs

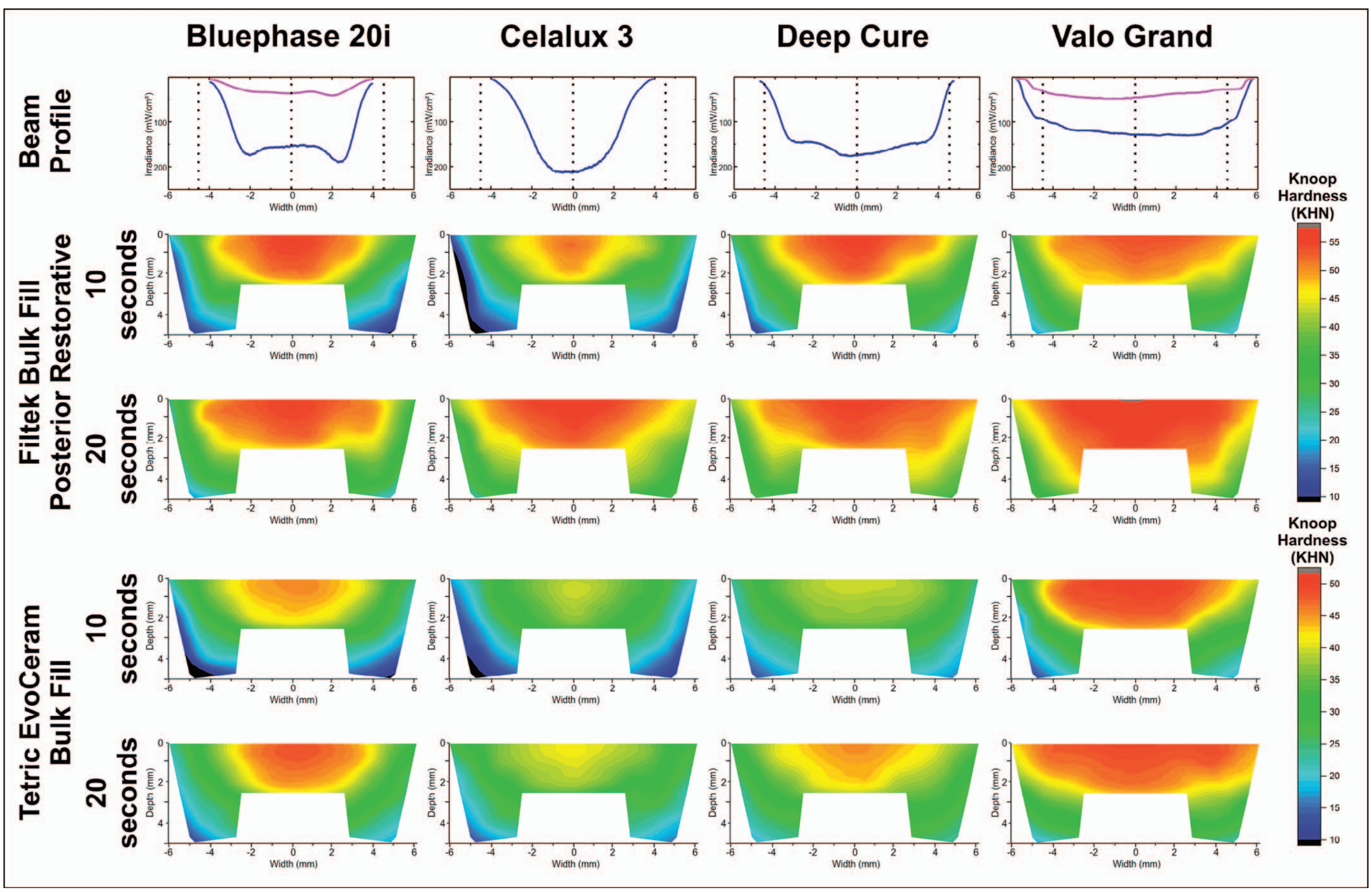


Figure 4. *Hardness maps made for both resin-based composites (RBCs) and both exposure times compared to the profile of the light that covered the restorations. Dotted lines over the beam profile of the lights represent the regions (central, mesial, and distal) where the indentations of the microhardness tests were made in the RBC specimens. The violet lines in the beam profile images indicate the violet light emission (<425 nm), and the blue lines indicate the blue light emission across the light tip.*

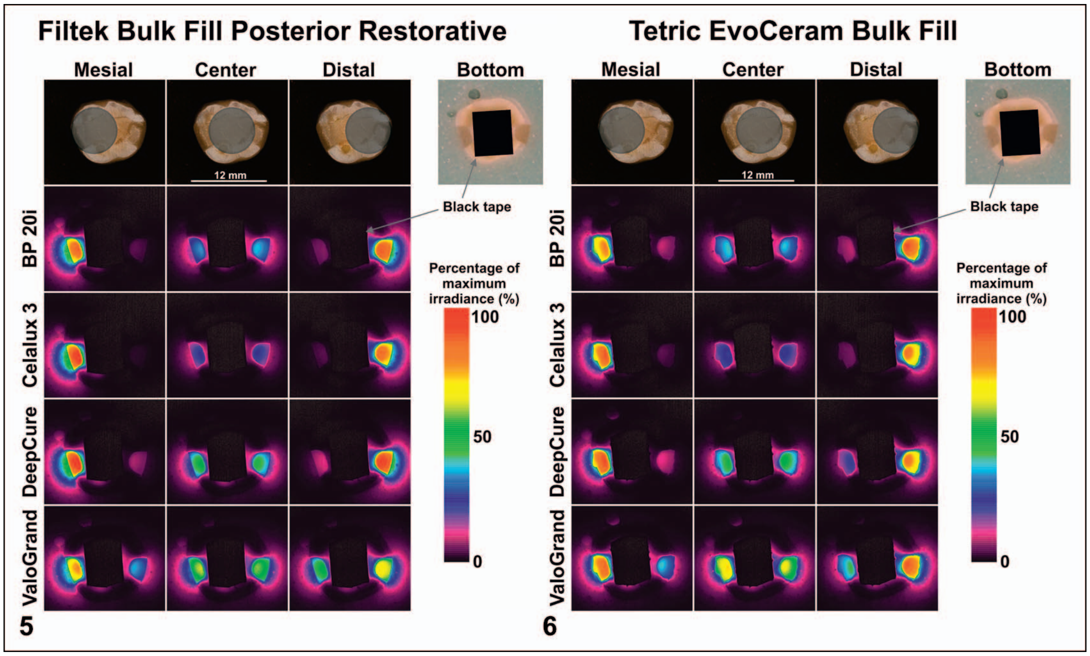


Figure 5. *Light transmission through restorations made with Filtek Bulk Fill Posterior, varying the position of the light-curing unit tip over the restoration. The image shows the light that reached the bottom of the proximal boxes in each light condition. An image of the bottom of the mold is also presented. Opaque black tape was used to prevent light from being transmitted through the occlusal region. BP 20i, Bluephase 20i; CL 3, Celalux 3; DC-S, Elipar Deep Cure-S; VG, Valo Grand.*

Figure 6. *Light transmission through restorations made with Tetric EvoCeram Bulk Fill, varying the position of the light-curing unit tip over the restoration. The image shows the light that reached the bottom of the proximal boxes in each light condition. An image of the bottom of the mold is also presented. Opaque black tape was used to prevent light from being transmitted through the occlusal region. BP 20i, Bluephase 20i; CL 3, Celalux 3; DC-S, Elipar Deep Cure-S; VG, Valo Grand.*

was positioned over one of the proximal boxes, more light reached to the bottom of that box, but very little light reached the opposite proximal box, independent of which of the RBC was used (Figures 5 and 6).

DISCUSSION

The LCUs used in this study were chosen because they had different light tip diameters and different light-emitting characteristics (Table 1). These differences influenced the Knoop microhardness results, and thus, the first null hypothesis that the LCUs would not affect the curing profile of the bulk-fill RBC restorations was rejected. The exposure time also influenced the microhardness results. Thus, the second null hypothesis, that a 20-second exposure time would not improve the curing profile of the bulk-fill RBC restorations was also rejected.

Influence of Tip Diameter

The observation that the different LCUs would have different effects on the hardness maps of the two RBCs was anticipated and supported previous studies.[10,11,19] In general, the use of LCUs with wider tips (Elipar Deep Cure-S and Valo Grand) produced more homogeneous hardness maps, as evidenced by the higher hardness values measured at the proximal boxes, compared to the Bluephase 20i and Celalux 3 LCUs that had the smaller diameter light tips (Tables 4 to 7). When the light tip diameter and the curing profiles are examined, it can be seen that the RBC under the center of the LCU was hard. Thus, the tip diameter would not be an issue when using a filling technique that places and photocures 2-mm increments of RBC into cavities or when using the ISO 4049 4-mm diameter mold because the LCU tip would cover the entire increment of the RBC. However, the tip diameter does become a problem when the operator attempts to photocure an entire molar MOD restoration in a tooth using a single exposure from the occlusal surface.[7]

It is important to consider the difference between the external tip diameter and the regions of the LCUs tip from where light is actually emitted since even a small decrease in the tip diameter will produce a substantial reduction in the area and thus increase the radiant exitance.[7] All the evaluated LCUs had discrepancies between the effective and

Table 4: *Means ± Standard Deviations of the Knoop Microhardness results for Filtek Bulk Fill Posterior photoactivated for 10 seconds, measured at each region of the restoration (central, mesial [4.5 mm away from the center], and distal [4.5 mm away from the center]), comparing the different LCUs and depths (analysis made comparing each region separately)*[a]

Depth	Mesial				Central	
	BP 20i	Celalux 3	Deep Cure	Valo Grand	BP 20i	Celalux 3
0.5	45.3 ± 4.3 Ba	39.0 ± 1.9 Ca	50.1 ± 0.8 Aa	50.4 ± 0.5 Aa	55.3 ± 1.4 Aa	53.6 ± 1.7 Aa
1.0	43.1 ± 3.8 Bab	38.2 ± 1.8 Ca	48.8 ± 1.3 Aab	49.4 ± 0.9 Aa	53.8 ± 0.9 Ab	52.5 ± 1.9 Ab
1.5	41.2 ± 3.2 Bbc	37.0 ± 1.4 Cab	47.4 ± 1.7 Abc	48.1 ± 1.3 Aab	52.1 ± 1.2 Ac	51.6 ± 1.6 Ac
2.0	39.7 ± 2.0 Bc	35.0 ± 1.6 Cb	45.7 ± 2.0 Acd	46.3 ± 0.8 Abc	51.6 ± 1.3 Ac	50.4 ± 2.2 Ad
2.5	35.5 ± 1.4 Bd	32.3 ± 2.2 Bc	43.3 ± 1.7 Ad	43.8 ± 1.4 Ac		
3.0	32.6 ± 1.5 Be	28.7 ± 3.2 Cd	40.2 ± 0.7 Ae	41.1 ± 1.7 Ad		
3.5	29.1 ± 2.2 Bf	26.5 ± 2.6 Bd	36.1 ± 1.1 Af	38.0 ± 1.2 Ae		
4.0	26.0 ± 2.0 Bg	22.9 ± 2.0 Be	31.5 ± 1.6 Ag	34.0 ± 0.6 Af		

[a] *Different uppercase letters indicate statistical differences within rows (light curing units); different lowercase letters indicate statistical differences within columns ($p < 0.05$). N = 5 repeats.*

Table 5: *Means ± Standard Deviations of the Knoop Microhardness Results for Filtek Bulk Fill Posterior photoactivated for 20 seconds, measured at each region of the restoration (central, mesial [4.5 mm away from the center], and distal [4.5 mm away from the center]), comparing the different LCUs and depths (analysis made comparing each region separately)*[a]

Depth	Mesial				Central	
	BP 20i	Celalux 3	Deep Cure	Valo Grand	BP 20i	Celalux 3
0.5	48.3 ± 0.7 Ba	48.2 ± 0.3 Ba	54.4 ± 1.3 Aa	55.5 ± 1.4 Aa	55.2 ± 1.1 Ba	55.4 ± 0.7 Ba
1.0	47.2 ± 0.7 Bab	47.5 ± 0.3 Ba	53.5 ± 1.3 Aab	54.5 ± 1.1 Aab	54.5 ± 0.9 Bb	54.6 ± 0.8 Bb
1.5	46.1 ± 0.7 Bbc	46.0 ± 0.4 Bb	52.9 ± 1.3 Ab	53.5 ± 1.1 Abc	53.6 ± 0.9 Bc	53.9 ± 0.8 Bc
2.0	44.9 ± 0.6 Bc	44.8 ± 1.0 Bb	52.4 ± 1.4 Abc	52.6 ± 1.0 Ac	52.7 ± 1.0 Bd	53.2 ± 0.7 Bd
2.5	43.2 ± 0.7 Bd	42.8 ± 1.0 Bc	51.5 ± 1.2 Ac	50.7 ± 1.7 Ad		
3.0	40.6 ± 0.8 Be	40.7 ± 1.1 Bd	50.0 ± 1.7 Ad	48.9 ± 1.7 Ae		
3.5	37.5 ± 0.3 Bf	38.0 ± 0.7 Be	47.7 ± 1.0 Ae	46.3 ± 1.3 Af		
4.0	34.1 ± 0.5 Bg	35.2 ± 1.3 Bf	45.1 ± 1.4 Af	43.5 ± 1.0 Ag		

[a] *Different uppercase letters indicate statistical differences within rows (light curing units); different lowercase letters indicate statistical differences within columns ($p < 0.05$). N = 5 repeats.*

Table 6: *Means ± Standard Deviations of the Knoop Microhardness Results for Tetric EvoCeram Bulk Fill photoactivated for 10 seconds, measured at each region of the restoration (central, mesial [4.5 mm away from the center], and distal [4.5 mm away from the center]), comparing the different LCUs and depths (analysis made comparing each region separately)*[a]

Depth	Mesial				Central	
	BP 20i	Celalux 3	Deep Cure	Valo Grand	BP 20i	Celalux 3
0.5	34.3 ± 3.1 Ba	26.7 ± 1.8 Ca	35.6 ± 0.8 Ba	43.6 ± 1.2 Aa	45.1 ± 1.0 Ba	40.9 ± 1.6 Ca
1.0	32.6 ± 1.9 Bab	25.3 ± 1.8 Cab	33.6 ± 0.7 Bb	42.3 ± 1.6 Aa	43.4 ± 0.8 Bb	39.5 ± 1.3 Ca
1.5	32.1 ± 1.1 Bb	24.1 ± 1.5 Cbc	32.3 ± 0.7 Bbc	40.4 ± 1.2 Ab	41.9 ± 1.3 Bc	37.8 ± 1.3 Cb
2.0	30.5 ± 1.5 Bc	22.8 ± 1.9 Ccd	30.7 ± 0.4 Bc	37.5 ± 1.4 Ac	39.7 ± 2.5 Bd	37.0 ± 0.9 Cc
2.5	27.9 ± 1.3 Bd	21.5 ± 1.7 Cd	28.5 ± 1.0 Bd	34.8 ± 2.1 Ad		
3.0	25.9 ± 1.0 Be	19.2 ± 0.7 Ce	26.5 ± 1.0 Be	31.9 ± 2.5 Ae		
3.5	24.0 ± 1.3 Bf	16.7 ± 0.6 Cf	24.6 ± 0.7 Bf	28.4 ± 1.1 Af		
4.0	20.6 ± 1.3 Bg	14.4 ± 0.5 Cg	21.9 ± 0.3 Bg	24.9 ± 1.2 Ag		

[a] *Different uppercase letters indicate statistical differences within rows (light curing units); different lowercase letters indicate statistical differences within columns ($p < 0.05$). N = 5 repeats.*

Table 4: *Means ± Standard Deviations of the Knoop Microhardness results for Filtek Bulk Fill Posterior photoactivated for 10 seconds, measured at each region of the restoration (central, mesial [4.5 mm away from the center], and distal [4.5 mm away from the center]), comparing the different LCUs and depths (analysis made comparing each region separately) (ext.)*

Depth	Central		Distal			
	Deep Cure	Valo Grand	BP 20i	Celalux 3	Deep Cure	Valo Grand
0.5	55.8 ± 1.2 Aa	54.1 ± 1.6 Aa	33.4 ± 1.8 Ca	32.6 ± 1.3 Ca	42.1 ± 1.3 Ba	47.1 ± 2.4 Aa
1.0	54.6 ± 0.8 Ab	53.1 ± 1.6 Ab	32.2 ± 1.8 Ca	31.4 ± 1.7 Cab	40.7 ± 1.2 Bab	45.4 ± 2.2 Aa
1.5	53.5 ± 0.8 Ac	51.9 ± 1.7 Ac	30.2 ± 2.3 Cb	30.1 ± 2.3 Cbc	38.9 ± 1.7 Bb	43.4 ± 1.9 Ab
2.0	52.6 ± 1.1 Ad	50.7 ± 1.6 Ad	28.6 ± 2.5 Cbc	28.4 ± 1.5 Cc	36.6 ± 1.7 Bc	41.5 ± 1.8 Ac
2.5			27.1 ± 2.4 Cc	26.3 ± 1.5 Cd	33.8 ± 1.6 Bd	39.2 ± 1.6 Ad
3.0			24.4 ± 1.6 Cd	23.8 ± 1.1 Ce	31.2 ± 1.7 Be	35.4 ± 1.7 Ae
3.5			21.3 ± 2.6 Ce	20.9 ± 1.9 Cf	27.8 ± 1.4 Bf	31.3 ± 1.4 Af
4.0			19.1 ± 2.9 Cf	17.5 ± 2.3 Cg	23.3 ± 0.9 Bg	26.9 ± 1.8 Ag

Table 5: *Means ± Standard Deviations of the Knoop Microhardness Results for Filtek Bulk Fill Posterior photoactivated for 20 seconds, measured at each region of the restoration (central, mesial [4.5 mm away from the center], and distal [4.5 mm away from the center]), comparing the different LCUs and depths (analysis made comparing each region separately) (ext.)*

Depth	Central		Distal			
	Deep Cure	Valo Grand	BP 20i	Celalux 3	Deep Cure	Valo Grand
0.5	57.9 ± 0.9 Aa	58.6 ± 0.7 Aa	46.5 ± 0.3 Ba	47.0 ± 1.0 Ba	52.2 ± 0.3 Aa	53.3 ± 1.3 Aa
1.0	56.9 ± 1.2 Ab	57.6 ± 0.9 Ab	45.6 ± 0.3 Bab	46.3 ± 1.1 Bab	51.1 ± 0.3 Aab	52.4 ± 1.2 Aab
1.5	56.0 ± 1.0 Ac	56.8 ± 1.0 Ac	44.5 ± 0.5 Bbc	45.3 ± 1.0 Bb	50.3 ± 0.8 Abc	51.6 ± 1.4 Ab
2.0	55.1 ± 1.2 Ad	56.2 ± 0.9 Ad	43.5 ± 0.7 Bc	43.5 ± 1.2 Bc	49.5 ± 0.8 Ac	50.9 ± 1.4 Abc
2.5			41.9 ± 0.9 Bd	41.6 ± 1.4 Bd	47.9 ± 1.1 Ad	49.7 ± 1.5 Ac
3.0			40.0 ± 1.1 Be	39.1 ± 1.5 Be	45.6 ± 1.1 Ae	47.2 ± 1.6 Ad
3.5			37.2 ± 1.2 Cf	36.0 ± 1.9 Cf	42.8 ± 1.4 Bf	45.6 ± 0.9 Ae
4.0			34.0 ± 1.0 Cg	33.3 ± 1.3 Cg	40.1 ± 1.3 Bg	42.9 ± 0.9 Af

Table 6: *Means ± Standard Deviations of the Knoop Microhardness Results for Tetric EvoCeram Bulk Fill photoactivated for 10 seconds, measured at each region of the restoration (central, mesial [4.5 mm away from the center], and distal [4.5 mm away from the center]), comparing the different LCUs and depths (analysis made comparing each region separately) (ext.)*

Depth	Central		Distal			
	Deep Cure	Valo Grand	BP 20i	Celalux 3	Deep Cure	Valo Grand
0.5	40.7 ± 0.9 Ca	47.9 ± 1.3 Aa	29.6 ± 3.2 Ba	22.7 ± 1.5 Ca	30.2 ± 0.3 Ba	41.3 ± 2.1 Aa
1.0	39.5 ± 0.8 Cab	46.7 ± 1.2 Aab	27.3 ± 2.8 Bb	21.3 ± 1.0 Cab	28.4 ± 0.5 Bab	39.1 ± 2.1 Aa
1.5	38.5 ± 0.8 Cbc	45.5 ± 1.7 Ab	25.7 ± 2.0 Bbc	19.9 ± 1.6 Cbc	26.7 ± 1.3 Bbc	35.5 ± 2.0 Ab
2.0	37.6 ± 0.8 BCc	43.5 ± 2.7 Ac	24.1 ± 1.2 Bc	17.9 ± 1.0 Ccd	24.9 ± 0.9 Bcd	31.8 ± 1.5 Ac
2.5			21.7 ± 0.9 Bd	16.5 ± 1.0 Cd	23.5 ± 1.1 Bd	29.7 ± 1.8 Ac
3.0			18.9 ± 2.1 Be	13.7 ± 1.1 Ce	21.2 ± 1.6 Be	25.1 ± 1.3 Ad
3.5			16.8 ± 1.7 Be	12.0 ± 0.6 Cef	20.1 ± 1.9 Ae	21.3 ± 0.9 Ae
4.0			14.1 ± 1.1 Bf	10.0 ± 0.6 Cf	17.8 ± 1.8 Af	18.7 ± 0.9 Af

Table 7: *Means ± Standard Deviations of the Knoop Microhardness Results for Tetric EvoCeram Bulk Fill photoactivated for 20 seconds, measured at each region of the restoration (central, mesial [4.5 mm away from the center], and distal [4.5 mm away from the center]), comparing the different LCUs and depths (analysis made comparing each region separately)*[a]

Depth	Mesial				Central	
	BP 20i	Celalux 3	Deep Cure	Valo Grand	BP 20i	Celalux 3
0.5	35.8 ± 1.9 Ca	33.1 ± 0.9 Da	42.1 ± 0.7 Ba	48.3 ± 0.3 Aa	47.0 ± 0.6 Ba	41.3 ± 0.6 Da
1.0	34.8 ± 1.6 Cab	32.4 ± 0.8 Dab	41.0 ± 0.6 Ba	46.9 ± 0.5 Ab	46.0 ± 0.6 Bb	40.6 ± 0.6 Db
1.5	33.8 ± 1.7 Cbc	31.4 ± 1.0 Db	39.5 ± 1.1 Bb	45.0 ± 0.7 Ac	45.1 ± 0.4 Bc	39.8 ± 0.6 Cc
2.0	32.5 ± 1.3 Cc	30.0 ± 1.2 Dc	38.4 ± 1.2 Bbc	42.0 ± 1.1 Ad	44.0 ± 0.5 Bd	39.2 ± 0.6 Cd
2.5	30.6 ± 1.7 Bd	28.6 ± 0.6 Cd	37.3 ± 1.1 Ac	38.8 ± 2.0 Ae		
3.0	28.7 ± 1.3 Be	25.8 ± 1.3 Ce	35.3 ± 0.9 Ad	36.0 ± 2.0 Af		
3.5	25.5 ± 0.9 Bf	24.1 ± 1.1 Bf	32.9 ± 1.4 Ae	32.7 ± 1.1 Ag		
4.0	23.4 ± 1.0 Bg	21.9 ± 0.9 Bg	31.0 ± 1.0 Af	30.2 ± 0.8 Ah		

[a] *Different uppercase letters indicate statistical differences within rows (light curing units); different lowercase letters indicate statistical differences within columns ($p < 0.05$). N = 5 repeats.*

the external tip diameters. This difference was as much as 3.4 mm for Valo Grand (Table 1) and may lead the user to erroneously believe that the whole restoration surface is being covered by light.

Radiant Exitance and Light Beam Profile

Another characteristic of LCUs that influences the polymerization of the RBCs is the irradiance beam profile of the light emitted from the LCU.[10,11] The light beam profile provides information about the distribution of the irradiance from the LCU.[9] It has already been shown that when very high irradiance values, above 1500 mW/cm^2, are received, this may lead to a lower degree of conversion the material.[21,22] Also, as the distance between the LCU tip and the RBC increases, the irradiance received by the RBC decreases.[23,24] In the present study, instead of light-curing at a 0-mm distance, the tip of the LCUs was fixed at a 2-mm distance because the cusp tips had been ground flat. Thus, this 2-mm distance represented the clinical distance between the cusp tip and the central fossa.

This study suggests that LCUs that have a wide tip diameter and deliver a more homogeneous light output should be used when photocuring large bulk-fill restorations since these LCUs will produce more uniform hardness values across the restoration.[10,11,19] Although smaller-diameter light tips may produce acceptable results when using a 4 mm diameter mold in the ISO 4049 test, the use of nonhomogeneous lights with narrow tip diameters will lead to inhomogeneous hardness results in MOD restorations in the tooth. This is illustrated by the nonuniform distribution of colors in the hardness maps in Figure 4. In addition to the discrepancy between the effective and the external tip dimensions, a nonuniform light beam profile may also lead to errors when trying to cover the restoration with the light adequately. Notably, the scaled irradiance color scheme in Figure 3 shows that, although the external tip diameter of the Celalux 3 is 8 mm, the effective tip diameter is 7.1 mm, and only the center 4-mm diameter produces a radiant exitance that is greater than 400 mW/cm^2. This can be observed by the increased amount of green, yellow, and red colors representing the higher irradiance values at the center of the LCU tip in Figure 3.

Emission Spectrum

Since it is known that the emission spectrum from the LCUs can influence the curing and microhardness of RBC restorations[25] the two different RBCs tested in this study were chosen because they use different photoinitiator systems. Filtek Bulk Fill Posterior uses only the type II initiator CQ, whereas Tetric EvoCeram Bulk Fill uses a combination of type II (CQ) and type I (Ivocerin) initiators. Although Ivocerin has its absorption peak close to 412 nm within the region of violet light, its absorption is different from other alternative type I initiators, such as Lucirin TPO, which absorb light mainly in the UV range, because Ivocerin is activated by wavelengths of blue light up to 460 nm.[14] In addition, since Ivocerin is a Type I photoinitiator and is a more efficient photoactivator compared to CQ[26], the curing profile of the two tested RBCs was anticipated to be different. Thus the fact that the multiple-peak LCUs (Bluephase 20i and Valo Grand) that both emitted violet light produced higher microhardness results than the use of the single-peak blue LCUs (Celalux 3 and Elipar DeepCure-S) was anticipated. However, this was only evident at

Table 7: *Means ± Standard Deviations of the Knoop Microhardness Results for Tetric EvoCeram Bulk Fill photoactivated for 20 seconds, measured at each region of the restoration (central, mesial [4.5 mm away from the center], and distal [4.5 mm away from the center]), comparing the different LCUs and depths (analysis made comparing each region separately) (ext.)*

Depth	Central		Distal			
	Deep Cure	Valo Grand	BP 20i	Celalux 3	Deep Cure	Valo Grand
0.5	45.5 ± 0.8 Ca	51.0 ± 1.0 Aa	34.3 ± 1.9 Ca	32.5 ± 0.8 Ca	38.4 ± 1.2 Ba	47.2 ± 1.3 Aa
1.0	44.8 ± 0.7 Cb	50.2 ± 0.9 Ab	33.3 ± 1.4 Cab	31.5 ± 0.6 Ca	37.3 ± 1.1 Ba	46.5 ± 1.1 Aab
1.5	44.0 ± 0.7 Bc	49.3 ± 0.6 Ac	31.9 ± 1.7 Cb	30.2 ± 0.7 Cb	35.8 ± 1.1 Bb	45.3 ± 1.3 Ab
2.0	43.2 ± 0.7 Bd	48.5 ± 0.6 Ad	30.4 ± 1.4 Cc	28.3 ± 0.8 Cc	34.7 ± 1.6 Bb	43.6 ± 1.0 Ac
2.5			28.4 ± 1.7 Cd	27.2 ± 0.9 Cc	33.3 ± 1.6 Bc	40.5 ± 1.4 Ad
3.0			26.7 ± 2.1 Ce	25.2 ± 1.0 Cd	31.2 ± 1.4 Bd	37.5 ± 0.8 Ae
3.5			24.8 ± 1.5 Cf	23.5 ± 1.1 Ce	29.2 ± 1.7 Be	34.2 ± 0.9 Af
4.0			21.9 ± 1.1 Cg	20.6 ± 1.0 Cf	27.4 ± 1.3 Bf	30.9 ± 0.5 Ag

the at the center of the Tetric EvoCeram Bulk Fill restorations where the RBC was 2 mm thick. At the proximal boxes, the violet light had no beneficial effect, and the tip diameter had a greater impact over microhardness results. Since the emission spectrum of the light emitted by the LCUs influenced the hardness results of one RBC, it is important to consider what wavelengths of light are effectively reaching the RBC at both the top and the bottom of the specimen. Thus, the beam profile of the violet light emitted at the tip of the LCUs and what light reaches the bottom of the RBC also becomes relevant.[27] Figure 3 shows that for the two multiple-peak lights used in this study, the beam profiles of the lights taken through the 400 nm filter show that violet light was emitted across the entire light tip, although at a much lower level than the blue light. As expected, since Filtek Bulk Fill Posterior does not require violet light, the microhardness results for Filtek Bulk Fill Posterior were not affected by the emission spectrum of the four different LCUs.

Exposure Time

To verify the effect of different exposure times on the curing profile of the restorations, both 10- and 20-second photoactivation times were used. A 10-second exposure was chosen according to the manufacturer's recommended time, but the specimens did not receive any exposures from the buccal and lingual surfaces.[28,29] When the exposure time was doubled to 20 seconds from the occlusal surface, the hardness results increased, and the curing profile became more homogeneous. This result was anticipated because it has been reported that the radiant exposure can be correlated to the degree of conversion of RBCs and that increasing the exposure time should result in increased photocuring, until a saturation point is reached.[25,30] This effect could be observed by the increase in the homogeneity of the hardness maps shown in Figure 4 independently of the LCU or the RBC used. This observation may raise doubts about the relevance of beam inhomogeneity on the photoactivation of RBCs since, when longer exposure times are used, the differences in the results of different materials photoactivated with different LCUs are reduced and may even disappear. However, any increase in exposure time beyond what is recommended by the manufacturer to improve the homogeneity of the curing profile of the composite resin should be done with caution because this longer exposure time will deliver more energy to the tooth. This may generate more heat in both the tissues adjacent to the restoration and the pulp.[26,31] Therefore, a short 5-second delay between multiple exposures is recommended to allow the tissues and tooth to cool.

Influence of the Mold

Overall, the microhardness values in the tooth were lower than anticipated, most notably at the bottom of the proximal boxes. The depth of cure of bulk-fill RBCs has already been well discussed,[4] but the width of cure, or curing profile in a tooth, has not.[5,19] However, a high methodological heterogeneity has been reported for the studies that have evaluated the depth of cure of bulk-fill RBCs[4], and it has been reported that the characteristics of the mold used can influence the results of RBC polymerization.[17,32,33] The material of which the mold is made can influence the light transmission and, consequently, the resin polymerization since more opaque materials will transmit less light.[17] The present study used a mold made using a human tooth to simulate a large MOD restoration, because it has been shown that use of tooth mold may result in higher depth of cure than opaque molds.[34] The use of a molar tooth mold was important to determine the influence of tip diameter and light beam profile on the curing profile of bulk-fill RBC restorations in real teeth. Although a previous study[15] reported that there were no differences between LCUs with different light beam profiles, the specimens used in that study were only 6 mm wide, and a 20-second exposure time was used. The fact that similar results were found in the present study at the center of the 12-mm wide RBC specimens, but not at the proximal boxes, highlights the clinical importance of the mold material and diameter on the conclusions of the study. Considering the results of the present study, if the ISO 4049 test using a 4-mm-diameter metal mold had been used, the polymerization of the RBCs would have appeared to be much better than what actually occurs in the proximal boxes of a MOD restoration in the tooth. But since the 4-mm-diameter metal mold[35] cannot reproduce the photoactivation of the RBC in extensive restorations, the ISO 4049 method for the depth of cure evaluation may even produce conclusions that are not clinically relevant.[18]

The mold design used in this study allowed the microhardness measurements to be made on the transverse surface of the restorations without requiring the specimens to be cut or polished. This was done because although many previous studies have evaluated the polymerization after cutting or polishing the specimens,[5,36] the use of water or ethanol may cause some dissolution of the monomers in the RBC, and this might affect the results.[37]

Although the LCUs were positioned at the center of restorations, differences were observed between the hardness values measured at the mesial and distal box regions of the restorations. The light distribution over the restoration, seen in Figure 3, showed that both areas received light similarly; therefore, it would be expected that the hardness of the restorations should be uniform, and no differences should be found between mesial and distal boxes. Also, the specimens were always positioned in the same position under the LCUs, and the jig and light clamping fixture prevented any alignment changes during the light-curing of specimens. However, a VPS matrix was used to standardize the shape of the restorations and to simulate the original tooth contour. Similar to the metallic matrices commonly used in the restoration of class II cavities that do not allow any additional light transmission from the proximal surfaces, the VPS matrix was opaque. Consequently, it is likely that the small differences observed were probably caused by the differences in the natural anatomical contour of the mesial and distal surfaces of the human tooth and the restorations.

Effective Tip Size in Relation to Restoration Dimensions

The Knoop microhardness values were low at the bottom of the proximal boxes for all the LCUs tested, as illustrated by the greater number of blue regions in the curing profiles (Figure 4). Although LCUs with wide tips and homogeneous beam profile, such as Valo Grand and Elipar DeepCure-S, delivered better results in the proximal boxes than LCUs with narrow tips and an inhomogeneous beam profile, such as Bluephase 20i and Celalux 3, none of the LCUs produced hardness values that were acceptable (>80%)[38] at these regions. Instead, the hardness values at the bottom of the proximal boxes achieved by Celalux 3 used for 10 seconds were as low as 30% of the maximum hardness for Filtek Bulk Fill Posterior and only 20% of the maximum values achieved for Tetric EvoCeram Bulk Fill. The low hardness results at the bottom of the proximal boxes can be explained by the rather low amount of light that reached the bottom of the restoration (Figures 5 and 6). This occurred mainly when the LCUs with smaller tips were used. Because of the difficulty to access and see the restorations at the bottom of the proximal boxes and the low bond strength of poorly polymerized RBCs to the cervical area,[39] this region may be more susceptible to secondary caries,[40] increased solubility, and increased biofilm formation.[41]

The smaller-diameter area of light curing should not be an issue if an incremental filling and light-curing technique is used or even when considering the photoactivation of a restoration made with a bulk-fill RBC that is less than the effective diameter of the light tip. However, it becomes a problem when trying to bulk cure an extensive MOD restoration in a molar tooth. Instead of using a single light exposure at the center of the restoration, it is recommended that each proximal box be light-cured separately, even when larger-diameter light tips are used. By doing this, the clinician can ensure that all of the RBC they are trying to photocure is within the region covered by the effective internal diameter of the light tip.

Limitations

This study was conducted under ideal conditions. The LCUs had been tested and were working within the manufacturer's specification, and the LCU was correctly positioned and stabilized above the restoration. These ideal circumstances may not always occur clinically. The low indentation load used for the microhardness test may be considered a limitation, but this low load was necessary to prevent damage to the specimens and was compensated for by increasing the objective magnification (10×) so that the image of the indent filled the imaging screen. Another limitation was that the curing lights were positioned only at the center of the restoration. However, exposure times of both 10 and 20 seconds were used because according to the manufacturer's instructions,[28] the exposure time for Filtek Bulk Fill Posterior used in the restoration of class II cavities should be 10 seconds at the occlusal surface and an extra 10 seconds at the buccal and lingual surfaces provided that the LCU delivers a radiant exitance above 1000 mW/cm^2. The manufacturer of Tetric EvoCeram Bulk Fill recommends that class II cavities be photoactivated for 10 seconds at the occlusal surface,[29] and the photoactivation should also be completed from the buccal and lingual surfaces, again provided that the LCU delivers a radiant exitance above 1000 mW/cm^2. Although the light transmission through teeth is low, and additional photoactivation from buccal and lingual surfaces should increase the polymerization of the RBCs, especially at greater depths,[42] the amount of light transmitted through the buccal and lingual surfaces the teeth is unpredictable. Further studies are necessary to verify the value of additional light exposure through the tooth on the polymerization of the RBC in the proximal boxes. For example, should the mesial and distal boxes of molar teeth be exposed separately from both the buccal and lingual surfaces as well as from the central occlusal surface, making a total of five exposures?

CONCLUSIONS

Within the limitations of the present study, that used a human molar with a 12-mm mesial-distal length, a 2.5-mm deep occlusal box, and two 4.5-mm deep proximal boxes, wider curing light tip diameters, a more homogeneous light beam profile, and longer exposure times were found to be preferable when photoactivating MOD restorations made in this molar tooth. The Valo Grand, followed by the Bluephase 20i, produced the highest hardness values ($p<0.05$) at the center of the 12-mm wide specimens of Tetric EvoCeram Bulk Fill. Since less light reaches the bottom of the proximal boxes and the microhardness in these regions was negatively affected, light-curing from more than one location is recommended.

Acknowledgements

The authors wish to acknowledge the manufacturers who kindly donated the resin composites and the curing lights for this study.

Regulatory Statement

This study was conducted in accordance with all the provisions of the local human subjects oversight committee guidelines and policies of the Dalhousie University. The approval code issued for this study is: 2015-3632.

Conflict of Interest

The authors of this manuscript certify that they have no proprietary, financial, or other personal interest of any nature or kind in any product, service, and/or company that is presented in this article.

(Accepted 1 August 2019)

REFERENCES

1. Van Ende A, De Munck J, Lise DP, & Van Meerbeek B (2017) Bulk-fill composites: A review of the current literature *Journal of Adhesive Dentistry* **19(2)** 95-109, 10.3290/j.jad.a38141.
2. Ilie N & Stark K (2014) Curing behaviour of high-viscosity bulk-fill composites *Journal of Dentistry* **42(8)** 977-985, 10.1016/j.jdent.2014.05.012.
3. Fronza BM, Rueggeberg FA, Braga RR, Mogilevych B, Soares LE, Martin AA, Ambrosano G, & Giannini M (2015) Monomer conversion, microhardness, internal marginal adaptation, and shrinkage stress of bulk-fill resin composites *Dental Materials* **31(12)** 1542-1551, 10.1016/j.dental.2015.10.001.
4. Lima RBW, Troconis CCM, Moreno MBP, Murillo-Gomez F, & De Goes MF (2018) Depth of cure of bulk fill resin composites: A systematic review *Journal of Esthetic and Restorative Dentistry* **30(6)** 492-501, 10.1111/jerd.12394.
5. Li X, Pongprueksa P, Van Meerbeek B, & De Munck J (2015) Curing profile of bulk-fill resin-based composites *Journal of Dentistry* **43(6)** 664-672, 10.1016/j.jdent.2015.01.002.
6. van Dijken JWV & Pallesen U (2017) Bulk-filled posterior resin restorations based on stress-decreasing resin technology: A randomized, controlled 6-year evaluation *European Journal of Oral Sciences* **125(4)** 303-309, 10.1111/eos.12351.
7. Shimokawa CA, Turbino ML, Harlow JE, Price HL, & Price RB (2016) Light output from six battery operated dental curing lights *Material Science and Engineering C-*

Materials for Biological Applications **69** 1036-1042, 10.1016/j.msec.2016.07.033.

8. Soares CJ, Braganca GF, Pereira R, Rodrigues MP, Braga SSL, Oliveira LRS, Giannini M, & Price RB (2018) Irradiance and radiant exposures delivered by LED light-curing units used by a left and right-handed operator *Brazilian Dental Journal* **29(3)** 282-289, 10.1590/0103-6440201802127.

9. Price RB, Ferracane JL, & Shortall AC (2015) Light-curing units: A review of what we need to know *Journal of Dental Research* **94(9)** 1179-1186, 10.1177/0022034515594786.

10. Magalhaes Filho TR, Weig KM, Costa MF, Werneck MM, Barthem RB, & Costa Neto CA (2016) Effect of LED-LCU light irradiance distribution on mechanical properties of resin based materials *Material Science and Engineering C-Materials for Biological Applications* **63** 301-307, 10.1016/j.msec.2016.02.060.

11. Price RB, Labrie D, Rueggeberg FA, Sullivan B, Kostylev, I & Fahey J (2014) Correlation between the beam profile from a curing light and the microhardness of four resins *Dental Materials* **30(12)** 1345-1357, 10.1016/j.dental.2014.10.001.

12. Zorzin J, Maier E, Harre S, Fey T, Belli R, Lohbauer U, Petschelt A, & Taschner M (2015) Bulk-fill resin composites: Polymerization properties and extended light curing *Dental Materials* **31(3)** 293-301, 10.1016/j.dental.2014.12.010.

13. Palin WM, Leprince JG, & Hadis MA (2018) Shining a light on high volume photocurable materials *Dental Materials* **34(5)** 695-710, 10.1016/j.dental.2018.02.009.

14. Burtscher P (2013) Ivocerin® in comparison to camphorquinone *Report—Research and development, Schaan, Liechtenstein: Ivoclar Vivadent* **19** 11-15.

15. Rocha MG, de Oliveira D, Correa IC, Correr-Sobrinho L, Sinhoreti M, Ferracane JL, & Correr AB (2017) Light-emitting diode beam profile and spectral output influence on the degree of conversion of bulk fill composites *Operative Dentistry* **42(4)** 418-427, 10.2341/16-164-L.

16. Price RB, Rueggeberg FA, Harlow J, & Sullivan B (2016) Effect of mold type, diameter, and uncured composite removal method on depth of cure *Clinical Oral Investigations* **20(7)** 1699-1707, 10.1007/s00784-015-1672-4.

17. AlShaafi MM, AlQussier A, AlQahtani MQ, & Price RB (2018) Effect of mold type and diameter on the depth of cure of three resin-based composites *Operative Dentistry* **43(5)** 520-529, 10.2341/17-122-L.

18. Flury S, Hayoz S, Peutzfeldt A, Husler J, & Lussi A (2012) Depth of cure of resin composites: Is the ISO 4049 method suitable for bulk fill materials? *Dental Materials* **28(5)** 521-528, 10.1016/j.dental.2012.02.002.

19. Shimokawa CAK, Turbino ML, Giannini M, Braga RR, & Price RB (2018) Effect of light curing units on the polymerization of bulk fill resin-based composites *Dental Materials* **34(8)** 1211-1221, 10.1016/j.dental.2018.05.002.

20. Ophir-Spiricon (2018) BeamGage®—User guide *North Logan, UT: Ophir-Spiricon*.

21. Selig D, Haenel T, Hausnerová B, Moeginger B, Labrie D, Sullivan B, & Price RB (2015) Examining exposure reciprocity in a resin based composite using high irradiance levels and real-time degree of conversion values *Dental Materials* **31(5)** 583-93, 10.1016/j.dental.2015.02.010.

22. Feng L, Carvalho R, & Suh BI (2009) Insufficient cure under the condition of high irradiance and short irradiation time *Dental Materials* **25(3)** 283-289, 10.1016/j.dental.2008.07.007.

23. Price RB, Labrie D, Whalen JM, & Felix CM (2011) Effect of distance on irradiance and beam homogeneity from 4 light-emitting diode curing units *Journal of the Canadian Dental Association* **77** b9.

24. Corciolani G, Vichi A, Davidson CL, & Ferrari M (2008) The influence of tip geometry and distance on light-curing efficacy *Operative Dentistry* **33(3)** 325-331, 10.2341/07-94.

25. Shimokawa C, Sullivan B, Turbino ML, Soares CJ, & Price RB (2017) Influence of emission spectrum and irradiance on light curing of resin-based composites *Operative Dentistry* **42(5)** 537-547, 10.2341/16-349-L.

26. Rueggeberg FA, Giannini M, Arrais CAG, & Price RBT (2017) Light curing in dentistry and clinical implications: A literature review *Brazilian Oral Research* **31(Supplement 1)** e61, 10.1590/1807-3107BOR-2017.vol31.0061.

27. Issa Y, Watts DC, Boyd D, & Price RB (2016) Effect of curing light emission spectrum on the nanohardness and elastic modulus of two bulk-fill resin composites *Dental Materials* **32(4)** 535-550, 10.1016/j.dental.2015.12.017.

28. 3M Oral Care (2016) Filtek Bulk Fill Posterior Restorative—Instructions for use *St Paul, MN: 3M Oral Care*.

29. Ivoclar Vivadent (2017) Tetric EvoCeram Bulk Fill—Instructions for use *Schaan, Liechtenstein: Ivoclar Vivadent*.

30. Erickson RL, Barkmeier WW, & Halvorson RH (2014) Curing characteristics of a composite. Part 1: Cure depth relationship to conversion, hardness and radiant exposure *Dental Materials* **30(6)** e125-133, 10.1016/j.dental.2014.02.012.

31. Mouhat M, Mercer J, Stangvaltaite L, & Ortengren U (2017) Light-curing units used in dentistry: Factors associated with heat development-potential risk for patients *Clinical Oral Investigations* **21(5)** 1687-1696, 10.1007/s00784-016-1962-5.

32. Erickson RL & Barkmeier WW (2014) Curing characteristics of a composite. Part 2: The effect of curing configuration on depth and distribution of cure *Dental Materials* **30(6)** e134-145, 10.1016/j.dental.2014.02.013.

33. Harrington E & Wilson HJ (1993) Depth of cure of radiation-activated materials—Effect of mould material and cavity size *Journal of Dentistry* **21(5)** 305-311.

34. Church BW, Tantbirojn D, Do T, Wells MH, & Versluis A (2017) Depth-of-cure of bulk-fill composites cured in tooth or opaque substrate *International Journal of Experimental Dental Science* **6(2)** 68-73.

35. ISO-Standards (2019) ISO 4049 Dentistry—Polymer based restorative materials *Geneve: International Organization for Standardization*.

36. Eshmawi YT, Al-Zain AO, Eckert GJ, & Platt JA (2018) Variation in composite degree of conversion and micro-

flexural strength for different curing lights and surface locations *Journal of the American Dental Association* **149(10)** 893-902, 10.1016/j.adaj.2018.06.004.

37. Sunbul HA, Silikas N, & Watts DC (2016) Surface and bulk properties of dental resin- composites after solvent storage *Dental Materials* **32(8)** 987-997, 10.1016/j.dental.2016.05.007.

38. Watts DC, Amer O, & Combe EC (1984) Characteristics of visible-light-activated composite systems *British Dental Journal* **156(6)** 209-215.

39. Xu X, Sandras DA, & Burgess JO (2006) Shear bond strength with increasing light-guide distance from dentin *Journal of Esthetic and Restorative Dentistry* **18(1)** 19-27 discussion 28.

40. Brouwer F, Askar H, Paris S, & Schwendicke F (2016) Detecting secondary caries lesions: A systematic review and meta-analysis *Journal of Dental Research* **95(2)** 143-151, 10.1177/0022034515611041.

41. Maktabi H, Ibrahim M, Alkhubaizi Q, Weir M, Xu H, Strassler H, Fugolin APP, Pfeifer CS, & Melo MAS (2019) Underperforming light curing procedures trigger detrimental irradiance-dependent biofilm response on incrementally placed dental composites *Journal of Dentistry* **88(Sep)** 103110, doi:10.1016/j.jdent.2019.04.003.

42. Hamlin NJ, Bailey C, Motyka NC, & Vandewalle KS (2016) Effect of tooth-structure thickness on light attenuation and depth of cure *Operative Dentistry* **41(2)** 200-207, 10.2341/15-067-L.