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# Influence of Multiple Peak Light-emitting-diode Curing Unit Beam Homogenization Tips on Microhardness of Resin Composites

J Soto-Montero • G Nima • FA Rueggeberg • CTS Dias • M Giannini



### Clinical Relevance

Lack of beam homogeneity in multiwave light-curing units might produce inadequate polymerization in composite restorations, causing a decreased microhardness that lessens clinical longevity of a restoration. Light curing units producing homogeneous beams are recommended.


## SUMMARY

**This study evaluated the effect of light curing unit (LCU) guide type (regular or homogenizing) on top and bottom microhardness of conventional and bulk-fill resin-based composites (RBCs). A polywave light-emitting-diode (LED) LCU (Bluephase Style, Ivoclar Vivadent AG) was used with two different light guides: a regular tip (RT, 935 mW/cm$^2$ emittance) and a homogenizer tip (HT, 851 mW/cm$^2$ emittance). Two conventional RBCs (Herculite Ultra [HER], Kerr Corp; Tetric EvoCeram [TEC], Ivoclar Vivadent AG) and two bulk-fill RBCs (SonicFill [SOF], Kerr Corp; Tetric EvoCeram Bulk Fill [TBF], Ivoclar Vivadent AG) were tested. Disc-shaped samples (10 mm Ø), 2-mm thick for conventional composites and 4-mm thick for bulk-fill composites were prepared. Samples were light cured according to manufacturer-recommended times. Knoop microhardness values (KHN) were obtained on the top and bottom surfaces of each specimen at locations correlated with the output of the three LED chips emitting blue (456 nm) or violet light (409 nm). Beam profile analysis using both light guides was also performed. Microhardness of each composite was analyzed using three-way analysis of variance and Tukey honestly significant difference *post***



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***hoc* test (α=0.05). Beam profile images showed better light distribution across the surface of the HT light guide. Use of the HT decreased KHN of HER at the locations of the blue LED chips at bottom of the sample but had no effect on the top surface. For TEC, use of HT increased KHN of all three LED locations at the top surface. Use of the HT increased KHN of SOF at locations corresponding to one of the blue and the violet LED chips at the bottom surface. For TBF, HT increased KHN at all top surface locations. All RBCs showed higher mean KHN at the top compared with the bottom surfaces. In general, all composites presented a higher KHN at the blue LED areas regardless of the surface or the tip used. Results suggest that the homogenizer light guide resulted in significantly increased microhardness at the top, in composite resins containing alternative photoinitiators; however, that effect was not observed at the bottom surfaces.**

## INTRODUCTION

In most light-curing units (LCUs), radiation is transmitted from the source to the target surface using a nonflexible, removable, optic fiber light guide.[1–3] These guides, maintain the emitted light spectrum, such as used in some light-emitting-diode (LED) units preserving or enhancing the emittance.[2–5] The capability of the light guide to deliver the generated light spectrum and emittance has become important because use of the LED LCU has overtaken use of quartz-tungsten-halogen lights in most dental practices.[6–8]

LED LCUs contain one to four LED chips depending on the unit's design.[2] Some LCUs are capable of emitting blue and violet light within specific wavelength ranges, constituting what is known as "polywave," "multiple peak," or "multiwave" lights.[3,4,7] However, each chip produces light within a narrow spectral range, and some authors express concern regarding an uneven irradiance when using those LCUs.[5,6,9,10] Also, because each LED is placed at a specific location within the light-generating array, and little to no blending of the emitted beams occurs, a heterogeneous light distribution is produced at the emitting end of the guide.[5,6,9,11–16] This lack of uniformity within the emitted beam then exposes the target surface unevenly, producing a heterogeneous polymerization.[6,17] Thus, the target, light-curable restorative material may not receive light at all the emitted wavelengths and irradiance levels.[5–7,9,10,12]

The problem with a heterogeneous wavelength distribution of light becomes relevant with respect to the wide variety of photoinitiators used in resin-based materials: camphorquinone (CQ), 2,4,6-trimethylbenzoyldiphenyl phosphine oxide (TPO), bisacylphosphine oxide (BAPO), phenyl propanodione (PPD), and Ivocerin (Ivoclar Vivadent AG, Schaan, Liechtenstein).[2–4,18,19] Each of these photoinitiators responds preferably to light at specific wavelengths,[4,9,10,18,20] and a nonuniform wavelength distribution at the light emitting end might result in an incomplete or inconsistent polymerization of the target material due to lack of or partial activation of some photoinitiators.[6,9,10,12,21] Thus, a heterogeneous light distribution may result in localized areas of enhanced or reduced polymerization, which might be associated with clinical longevity of a restoration.[5,7,11,12,22] However, there is literature stating that a nonuniform light beam does not reduce the extent of polymerization in a 2-mm thick increment of CQ-based RBC and in composites containing up to 50% TPO in association with CQ.[14] In addition, it has been shown that increasing the polymerization time reduces the effect of the nonhomogeneity of the light beam on the degree of conversion of bulk-fill composites.[23] The lack of an effect has been attributed to special polymerization modifiers in bulk-fill composites, use of more efficient photoinitiator systems,[24,25] and overall enhanced light transmission in depth[24] by better matching of refractive indexes between filler particles and the resin components, which increase depth of cure.[25]

Clinically, an insufficient degree of monomer conversion in resin-based composites (RBCs) has been associated with decreased surface hardness,[5,12,26,27] discoloration,[9] reduced wear resistance,[5,28] lower bond strength,[9] cytotoxicity,[9] and a greater susceptibility to marginal gap defects.[9,29]

Relative comparison of the microhardness of the top and bottom surfaces of composite specimens has been proposed as an appropriate method to establish the effectiveness of light curing and as a way to study the polymerization of a specific material and its depth of cure using a particular curing condition.[27,30,31] This technique is valid because it has been reported that surface microhardness increases as the degree of conversion increases.[10,20,26,32] An international standards organization method uses measurement of the length of remaining, nonscrapable, perceptibly hardened composite as an indicator to assess adequacy of composite curing.[33] However, it is claimed that those methods overestimate composite depth of cure values because they only measure the deepest polymerized region of the RBC without considering the effects of differences in LED chip positions and differences in wavelengths reaching the restoration surface.[20,21,31,34]

In response to concerns about possible inadequate RBC polymerization, an LCU manufacturer developed a light guide to better homogenize the irradiance and emitted spectral distribution across the emitting tip end:[12] the homogenizer light guide, designed for use with a Polywave LCU.[35,36] This item is designed to reduce the light beam heterogeneity while maintaining the delivered power from the LCU. However, no scientific study has been performed to directly address these claims.

The purpose of this study was to analyze the effects of photopolymerizing different conventional and bulk-fill commercial composites with the same LCU body using a homogenizer light guide compared with a conventional (regular) guide tip. The effect of differences in the light guides was measured using microhardness of the top or bottom restoration surfaces. The working hypotheses were that (1) the use of the homogenizer light guide type would significantly influence microhardness of conventional and bulk-fill composites; (2) for the same light guide, lower wavelength light would produce reduced microhardness on conventional and bulk-fill composites, and (3) the microhardness at the top of the conventional and bulk-fill composite discs using either type of light guide would be significantly higher than at the bottom.

## METHODS AND MATERIALS

### LCU Characterization

A Polywave LCU (Bluephase Style, Ivoclar Vivadent AG, Schaan, Liechtenstein) with two blue LED chips (456 nm; B1 and B2) and one violet chip (409 nm, V) was used. One regular tip (RT) and one homogenizer tip (HT) light guide, each with a circular, 10-mm Ø (9.3 mm of active internal diameter), were commercially available for use in the same LCU. The spectral irradiance of the LCU between 350 and 550 nm was measured with each light guide five times using a 6″ National Institute of Standards and Technology–traceable, calibrated integrating sphere (CTSM-LSM-60-SF, Labsphere Inc, North Sutton, NH, USA), connected to a fiber optic spectrometer (USB 2000, Ocean Optics, Dunedin, FL, USA). Spectra were recorded using software (SpectraSuite version 1.4.2, Ocean Optics), and data were entered into a spreadsheet program (Excel 2016, Microsoft Corporation, Redmond, WA, USA). The RT light guide was considered the control.

The beam profile of the LCU when using both light guides was measured using a laser beam profiler with a 10-mm-diameter internal aperture. No imaging target was used; the light distribution across the emitting tip end was directly visualized. The LCU light guide was aligned using a profile camera with a 50-mm focal length lens (USB-L070, Ophir-Spiricon, Logan, UT, USA). Three measurements were performed using each light guide: one of the unfiltered beam profile, another one with a custom-made violet filter (International Light Technologies, Peabody, MA, USA) that only allows the passage of blue light in a 430-550 nm wavelength range, and a third with a custom-made blue filter (International Light Technologies) that only allows the passage of violet light in a 350-430 nm wavelength range. The resulting images of the unfiltered, violet-filtered and blue-filtered beam profiles were collected using software (Beamgage version 6.6, Ophir-Spiricon, North Logan).

### RBC Sample Preparation

Four commercial RBCs were tested. Two products were classified as conventional composites (indicated for increments 2-mm thick or less): Herculite Ultra (HER; Kerr Corporation, Orange, CA, USA) and Tetric EvoCeram (TEC; Ivoclar Vivadent AG). Two other materials were classified as high viscosity, bulk-fill materials intended for use in increments ranging from 4-mm to 5-mm thick: SonicFill (SOF; Kerr Corporation) and Tetric EvoCeram Bulk Fill (TBF; Ivoclar Vivadent AG). Product specifications are presented in Table 1.

Ten disc specimens (10-mm Ø, 2-mm thick) of each composite were fabricated using a polyvinyl siloxane impression material mold (Putty Soft, 3M Oral Care, St Paul, MN, USA) for the conventional composites (HER and TEC). For the bulk-fill products (SOF and TBF), the mold was 4-mm thick. All fabricated molds had three 0.5-mm notched extrusions on their inner walls, separated 120° from each other, which matched the locations of the LED chips at the proximal surface of the light guide: B1, B2, and V. Composites were placed in the matrix using a single increment, and a transparent polyester film was placed on the bottom and top surfaces of the composite-filled mold.[33] The assembly was lightly pressed between two microscope glass slides to remove excess composite. The specimen was placed

Table 1: *Classifications, Brand Names, Compositions, Exposure Time, Shades and Lot Numbers of Tested Materials*

| Classification | Composite (Abbreviations) | Composition | Photoinitiators | Exposure Time, s | Shade | Lot Number |
|---|---|---|---|---|---|---|
| Conventional RBC (increment of 2 mm or less) | Herculite Ultra (HER) | Bis-GMA, TEGDMA, Bis-EMA, silica and barium glass, prepolymer filler, titanium oxide, 4-methoxyphenol, BPO, trimethylolpropane triacrylate | CQ | 20 | A2 Dentin | 5444587 |
| | Tetric EvoCeram (TEC) | Bis-GMA, UDMA, barium glass, ytterbium trifluoride, prepolymer filler, mixed oxide | CQ, TPO | 10 | A2 Dentin | T22777 |
| Bulk-fill RBC (increments of 4 to 5 mm) | Sonic Fill (SOF) | Bis-GMA, TEGDMA, Bis-EMA, TMSPMA, barium glass, alumino-borosilicate glass | CQ | 20 | A2 | 5376244 |
| | Tetric EvoCeram Bulk Fill (TBF) | Bis-GMA, Bis-EMA, UDMA, alumino-borosilicate glass, prepolymer filler (ytterbium trifluoride), mixed oxides | CQ, TPO, Ivocerin | 10 | IVA | S51408 |

Abbreviations: RBC, resin-based composite; Bis-EMA, bisphenolglycidyl ethyl-methacrylate; Bis-GMA, bisphenolglycidyl methacrylate; BPO, benzoyl peroxide; CQ, camphorquinone; TEGDMA, triethylene glycol dimethacrylate; TMSPMA, 3-trimethoxysilylpropyl methacrylate; TPO, Diphenyl (2,4,6-trimethylbenzoyl) phosphine oxide; UDMA, urethane dimethacrylate.

over a white filter paper (Grade 1, Whatman, Little Chalfont, UK) background and slides were removed.[33] The LCU was fixed in a clamp and the distal end of the light guide was positioned perpendicular to the specimen at 1-mm distance from the upper polyester film surface to simulate a clinical scenario during posterior restoration. The light guide completely covered the specimen.

Light-activation for each composite followed the manufacturer's recommendations (Table 1). After light exposure, the specimens were removed from the molds, and locations on composite surfaces corresponding to the LED chip positions on the top and bottom surfaces were marked using a graphite pencil on the lateral wall of each specimen. The specimens were then stored in a dark oven (Fanen, Guarulhos, Brazil) for one hour at 36°C ± 1°C and then machine-polished (Aropol, Arotec Indústria e Comércio Ltda, Cotia, Brazil) using 1000-grit and 1200-grit abrasive paper (Wetordry, 3M, Sorocaba, Brazil) for 1 minute each, under water cooling. After polishing, specimens were again stored in the same dark oven for 24 hours before microhardness testing.

## Microhardness Test

A microhardness tester (Future-Tech FM Corp, Tokyo, Japan) coupled to software (FM-ARS 9000, Future-Tech FM Corp) was used to obtain Knoop hardness (KHN) values after applying a static load of 50 g (0.49 N) for five seconds to each composite surface. The average of three indentations, spaced at 100-μm distances from each other, at the central irradiant spot of each LED (Figure 1) were used to represent a single hardness value of that specific location for a given composite specimen. The location of the measurement area was determined using the notches made at the peripheral locations as reference, and from those locations, a displacement of 2.6 mm toward the center of the disc was defined as the starting point for Knoop indenter loading. The same protocol was followed for the top and bottom surfaces.

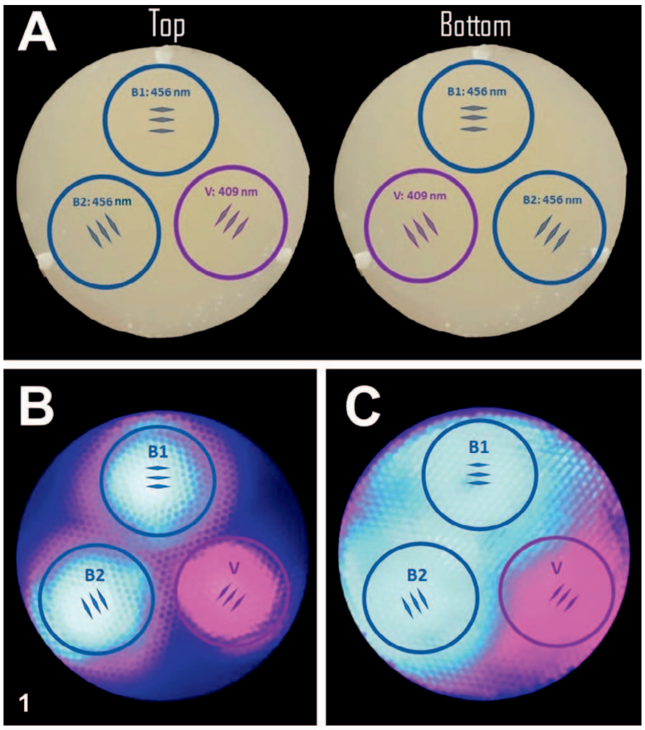
## Statistical Analysis

Spectral outputs and radiant emittances of the LCU with each light guide at different wavelength ranges were compared using the Student *t*-test ($p>0.05$). Due to the different compositions of the tested RBCs, statistical analysis of KHN was performed separately for each material using three-way analysis of variance (ANOVA) factors: surface (top or bottom), light guide (HT or RT), and LED wavelength (456 nm or 409 nm) using software (SAS 9.3 for Windows, SAS Institute, Cary, NC, USA). Microhardness values were averaged among the three measurements at each location. An exponential transformation of 1.5 was applied to obtain normality in the hardness data. The Tukey honestly significant difference *post hoc* multiple comparison test ($\alpha$=0.05) was applied to compare pairwise group means and interactions among factors within each RBC.

# RESULTS

## Spectral Irradiance and Beam Profiles

Measurements of wavelength ranges and means of the total power output and radiant exitances of the LED LCU using the RT and HT are presented in Table 2. Figure 2 shows the emission spectra of the two wavelengths of LEDs using the RT and HT light guides. Visual inspection of the beam profiles shows great differences in light output distribution and



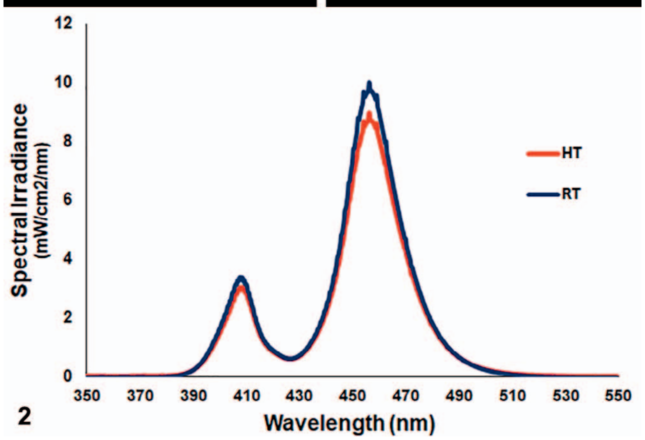




Figure 1. *Schematic representation for locations of microhardness measurements with respect to the specific LED chip that is emitting toward the proximal light guide end and from which light is emitted at the distal tip end (A): over the composite specimen, (B): at the output of the regular tip, and (C): al the output of the homogenizer tip.*

Figure 2. *Spectral irradiance profiles (mW/cm$^2$/nm) of the Bluephase Style LCU using the two different types of light guide tips. RT, regular tip; HT, homogenizer tip.*

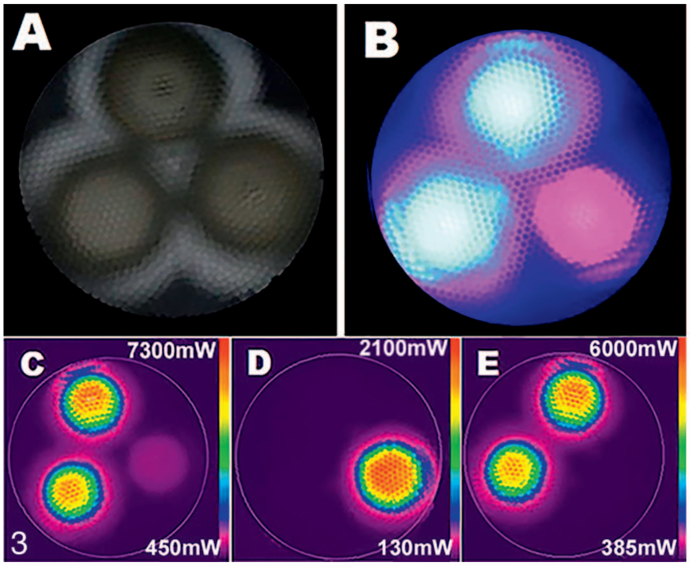
emittance between both light guides (Figures 3 and 4). Figure 3 shows that the individual LED chips using the RT are visible and separated from one another through the length of the light guide. The separation among LED chips, visible at the distal end with the light off, remains when the LCU is turned on, demonstrating the nonuniformity of the light output. The beam profile using the RT is characterized by the presence of two strong areas of emission corresponding to B1 and B2 LED chips and a weaker emission area corresponding to V in the unfiltered beam profile. Those areas of higher emittance corresponded directly with the central spot of each individual LED chip. The power concentrations at these locations contrasts with that of the large surrounding areas, where the presence of emitted light was practically undetectable, even when using filters.

When using the HT, the location of the individual emitting LED chips is barely visible at the end of the light guide (Figure 4). The separation between LED chips becomes visible when the LCU is turned on, also demonstrating an incomplete uniformity of light output. Nevertheless, as not seen when using the RT, the emitted blue and violet light is distributed across most of the light-emitting distal end of the HT. The beam profile using the HT is characterized by the presence of two locations of strong power emission, with a peak output of 2260 mW, corresponding to B1 and B2, and a weaker emission in the area corresponding to V. Although the high-power locations showed a greater concentration of light in the central spot of each 456-nm LED chip, the power output remained relatively homogeneous across the whole cross section of the light-emitting end of the guide. Filtered beam profile images showed the diffusion of energy emitted by each LED across a wide area. The area of low power output was practically nonexistent when using the HT.

## Surface Microhardness

Table 3 presents KHN results for the conventional composites HER and TEC. The three-way ANOVA for HER indicated that surface ($p<0.0001$), light guide type ($p<0.0001$), and wavelength ($p<0.0001$) significantly influenced the results, as well as the double interaction between light guide type and surface ($p<0.0001$) and light guide type and wavelength ($p=$ 0.0002). For TEC, statistical analysis showed that surface ($p<0.0001$) and wavelength ($p<0.0001$), as well as the double interaction between light guide type and surface ($p<0.0001$), significantly influenced KHN results. However, the type of light guide did not significantly influence the results.

Table 4 presents KHN results for the bulk-fill composites SOF and TBF. For SOF, the three-way ANOVA results indicated that surface ($p<0.0001$), light guide type ($p<0.0001$), and wavelength ($p<0.0001$) all significantly influenced the results, as well as the double interaction between surface and wavelength ($p=0.026$). Regarding TBF, surface



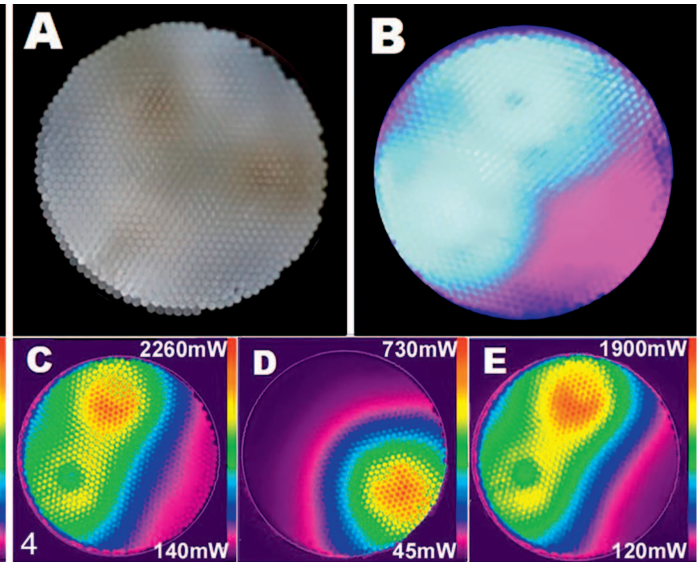




Figure 3. *Images of the distal end of the regular tip when inserted into the body of the Bluephase Style LCU. (A): LED with chips off. The location of the three LED chips can be seen through the light guide. (B): Light distribution from the LED chips across the regular tip when the LCU is on. Areas of blue and violet light emission can be distinguished, as well as areas of lower light levels. (C): Color-coded, scaled beam power profiles of the light emitted without using any bandpass filter. (D):Power distribution of only the violet chip using a 430-550 nm filter, and (E): Power distribution of only the blue light, using a 350-430 nm violet spectral filter placed in front of the camera lens of the beam profiler.*

Figure 4. *Images of the distal end of the homogenizer tip when inserted into the body of the Bluephase Style LCU (A): LED with chips off. The location of the three LED chips cannot be easily seen through the light guide. (B): Light distribution from the LED chips across the regular tip when the LCU is on. Areas of blue and violet light emission can be distinguished. (C): Color-coded, scaled beam power profiles of the light emitted without using any bandpass filter. (D): Power distribution of only the violet chip using a 430-550 nm filter, and (E): Power distribution of only the blue light, using a 350-430 nm filter placed in front of the camera lens of the beam profiler.*

($p<0.0001$), light guide type ($p<0.0001$), and wavelength ($p<0.0001$) significantly influenced KHN.

The bottom to top (B/T) hardness ratio of all the tested composites with the RT and the HT are presented in Figure 5. In general, for all the composites, KHN was higher at the top surface (0 mm) than those obtained at the bottom (2 or 4 mm thicknesses, according to composite type). Also, for both types of light guides, within the same surface (top and bottom), higher KHN was observed in areas irradiated by B1 and B2 than in locations of the V LED.

## DISCUSSION

The first working hypothesis stating that using the homogenizer light guide would produce differences in the KHN of composites was partially accepted. Except for TEC, KHN of all tested composites was significantly affected by the homogenizer light guide. The second working hypothesis, stating that for the same light guide, lower wavelength light would reduce the microhardness of composites, was also accepted. For all the tested RBCs and type of light guide, statistical analysis showed significant differences in KHN between locations irradiated mainly

Table 2: *Wavelength Range, Power Output, and Radiant Emittance of the Light-curing Unit Measured When Using the Different Types of Light Guide*[a]

| Wavelength Range, nm | Light Guide | Power Output, mW | Radiant Emittance, mW/cm$^2$ |
|---|---|---|---|
| 350-550 | RT | 635.8±1.3 A | 935.0±2.1 A |
| | HT | 578.0±1.0 B | 850.6±1.9 B |
| 350-430 | RT | 112.4±1.1 A | 165.8±1.8 A |
| | HT | 101.4±1.3 B | 148.8±1.1 B |
| 430-550 | RT | 523.0±1.0 A | 750.2±0.4 A |
| | HT | 476.4±0.5 B | 683.8±1.1 B |

*Abbreviations: RT, regular tip; HT, homogenizer tip.*
[a] *Different characters indicate significant difference among light guides for the same wavelength range within the same column by Student* t*-test* ($p>0.05$).

Table 3: *Microhardness of Conventional Composites HER and TEC According to LED Wavelength, Surface (Top and Bottom), and Tip Type*[a]

| Composite | LED Wavelength, nm | Tip Type | Surface | |
|---|---|---|---|---|
| | | | Top[b] | Bottom |
| HER | B1 (456) | RT | 59.1±3.3 Aa | 33.9±9.6 Aa |
| | | HT | 58.5±1.3 Aa | 20.4±3.3 Ba |
| | V (409) | RT | 47.0±4.4 Ab | 16.9±4.8 Ab |
| | | HT | 50.4±2.4 Ab | 14.2±2.9 Ab |
| | B2 (456) | RT | 59.4±5.1 Aa | 32.5±6.3 Aa |
| | | HT | 57.9±2.1 Aa | 19.7±2.7 Bab |
| TEC | B1 (456) | RT | 51.5±4.0 Ba | 46.6±4.2 Aa |
| | | HT | 55.5±3.4 Aa | 43.1±2.9 Aa |
| | V (409) | RT | 43.5±5.5 Bb | 36.0±5.7 Ab |
| | | HT | 49.8±3.2 Ab | 37.3±2.5 Ab |
| | B2 (456) | RT | 51.7±5.0 Ba | 46.3±5.9 Aa |
| | | HT | 55.4±3.3 Aa | 42.3±3.6 Ba |

*Abbreviations: LED, light-emitting diode; HER, Herculite; TEC, Tetric EvoCeram; B1, blue LED 1; V, violet LED; B2, blue LED 2; RT, regular tip; HT, homogenizer tip.*
[a] Statistical analysis was performed individually for each composite. Means followed by similar characters indicate no significant difference. Uppercase letters compare microhardness within the same composite, LED, and surface, using different light guides. Lowercase letters compare LED chips within the same composite, light guide, and surface.
[b] *KHN was significantly higher on the top surface of all composites within the same LED and tip.*

by the 409-nm violet LED and locations receiving blue light at 456 nm LED. The third hypothesis, stating that microhardness of composites would be higher at the top than at the bottom, was accepted because all tested composites exhibited significantly higher KHN at the top surface.

Four different composites were explored based on the different photoinitiator composition of the materials because HER and SOF are CQ-based composites, while TEC contains CQ and TPO, and TBF contains CQ, TPO, and Ivocerin. Given that beam profile analysis confirmed that the off-axis arrangement of the LED chips in the Polywave LCU results in a nonuniform beam, this study intended to test if the use of an HT would compensate for the beam heterogeneity, or if ,despite using the HT, differences in the KHN at the measurement locations of the top

Table 4: *Microhardness of Bulk-fill Composites SOF and TBF According to LED Wavelength, Surface (Top and Bottom), and Tip Type*[a]

| Composite | LED Wavelength, nm | Tip Type | Surface | |
|---|---|---|---|---|
| | | | Top[b] | Bottom |
| SOF | B1 (456) | RT | 63.2±1.4 Aa | 53.2±4.4 Aa |
| | | HT | 65.8±4.8 Aa | 54.6±2.2 Aa |
| | V (409) | RT | 58.9±2.3 Ab | 41.1±5.2 Bb |
| | | HT | 61.1±2.4 Ab | 47.6±3.0 Ab |
| | B2 (456) | RT | 63.4±2.6 Aa | 50.6±4.5 Ba |
| | | HT | 66.0±3.0 Aa | 53.8±1.6 Aa |
| TBF | B1 (456) | RT | 57.5±3.5 Ba | 50.8±4.1 Aa |
| | | HT | 62.8±4.7 Aa | 52.5±4.4 Aa |
| | V (409) | RT | 52.9±4.0 Bb | 45.1±2.5 Ab |
| | | HT | 57.2±4.8 Ab | 48.5±3.0 Ab |
| | B2 (456) | RT | 57.0±4.0 Ba | 49.0±3.6 Ba |
| | | HT | 63.6±5.5 Aa | 53.9±2.9 Aa |

*Abbreviations: LED, light-emitting diode; SOF, SonicFill; TBF, Tetric EvoCeram Bulk Fill; B1, blue LED 1; V, violet LED; B2, blue LED 2; RT, regular tip; HT, homogenizer tip.*
[a] *Statistical analysis was performed individually for each composite. Means followed by similar characters indicate no significant difference. Uppercase letters compare microhardness within the same composite, LED and surface, using different light guides. Lowercase letters compare LED chips within the same composite, light guide, and surface.*
[b] *KHN was significantly higher on the top surface of all composites within the same LED and tip.*

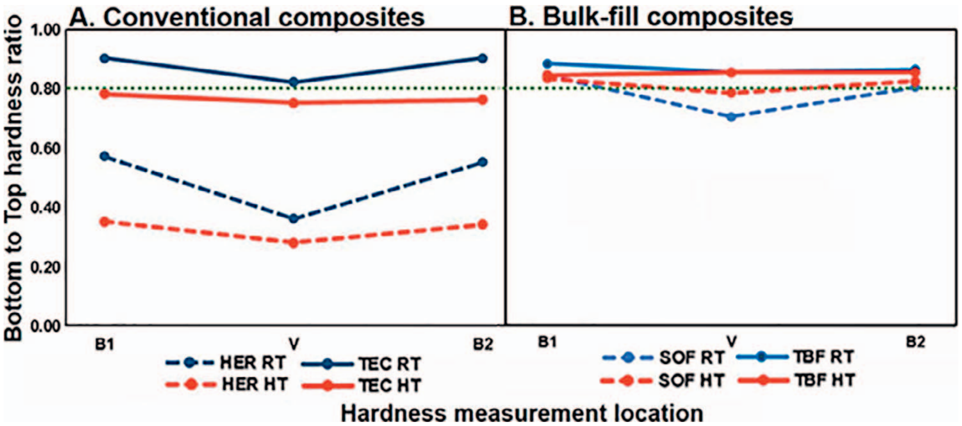



Figure 5. *Bottom to top hardness ratio of the (A): tested conventional and (B): bulk-fill composites with different light guide tips, according to location of Knoop microhardness measurement. RT, regular tip; HT, homogenizer tip.*

and bottom surfaces of the specimens would be observed.

An LCU should be able to adequately photopolymerize up to a 2-mm thickness of conventional composites. However, the B/T hardness ratio of the CQ-based conventional composite (HER) was below 0.6 when using either light guide. This value is below the recommended 0.8 necessary to consider the material adequately cured.[27,30] In the current study, the KHN of HER was higher when the RT was used, which might be a result of the high amount of light irradiating the composite from the center of the LED chips,[2–4,6,9,11] which matched the location of the KHN measurements. The spectral absorption range of CQ ranges from 425 to 490 nm, and matches the peak emission of the blue LEDs at 456 nm, but it has little sensitivity to violet light at 409 nm.[2] In our study, the KHN of HER was higher at the top surface and in the areas related to the output of the blue LEDs, which could be explained by the sensitivity of CQ to blue light and the lower penetration of the shorter-wavelength violet light.[10,16,22] These results diverge from the findings of a previous study where the curing profile of a conventional CQ-based composite was not influenced by using a nonhomogeneous, multiple-peak LCU up to a 2-mm depth.[14] However, it must be considered that the samples in that study were smaller (5×5 mm blocks with 3-mm thickness), and they were polymerized using an LCU producing a beam profile, which, despite not being completely homogeneous, spreads light in the absorption spectrum of CQ across most of the LCU output area.[14, 37] That aspect differs from the beam profile of the Bluephase Style LCU with both types of light guide tips used in this study.

The results for TEC showed that KHN was higher at the top surface and in locations corresponding with the positions of the blue LEDs, while the light guide type had no significant influence on hardness at the bottom surface, although the HT produced a higher KHN at the top surface at all measured locations. Because TEC contains both CQ and TPO photoinitiators, an improved sensitivity to violet light was expected,[10] and confirmed by the results. Using the RT produced a B/T ratio above 0.8 at all LED positions, and when using the HT, the B/T ratio was between 0.78 and 0.75. As explained previously, the higher B/T ratio observed using the RT might be a result of the power concentration at the locations correlated with the LED chips,[2,4,6,9,11] which resulted in lower light dispersion through the material. However, it was unexpected that the HT tip would fail to reach an acceptable B/T ratio at any of the measured locations, despite being used on a composite from the same manufacturer of the LCU, where a high sensitivity of the photoinitiators to the LCU emission spectrum is expected.[2,11,12] However, because KHN at the top surface was higher using the HT, the increase in top surface hardness influenced the B/T ratio calculation. Moreover, the effect of the HT in spreading the light beam produced a higher KHN at the top surface due to better activation of the alternative photoinitiators,[10] but the reduced concentration of irradiance in the measured locations may reduce the amount of light that reaches the bottom surface without dispersion, which along with the low penetrability of violet light[22] to activate TPO at a 2-mm thickness might be responsible for this result. The effect of a curing light on composite resin photopolymerization highly depends on the extent of localized emittance and the spectral homogeneity of the light beam.[12] Finally, the manufacturer of TEC recommends a maximum increment thickness of 1.5 mm for dentin shades, instead of the 2 mm used in the present study; as a result of that difference, KHN at the bottom might have been diminished, producing also a B/T ratio below the recommended value.

Based on these findings, clinicians should take care when polymerizing 2-mm-thick increments of conventional composites using a multiwave LCU, because the bottom surfaces may not receive sufficient energy to adequately polymerize the material. The reduced activation of photoinitiators due to nonhomogeneity of the light beam is known,[2,10,21] and therefore, it is recommended that clinicians match the emission spectrum of their LCU to the photoinitiator sensitivity of their chosen RBC.[2,3,19]

Analysis of the results using bulk-fill composites produced different findings than those of the conventional composites. Microhardness of SOF was higher at the bottom surface when using the HT in the location of the violet and one of the blue LEDs. Higher KHN at the top surface is an expected result because the top surface received higher irradiance than the bottom surface. Using both light guide types, the B/T ratio was above 0.8 at the locations of the blue LEDs and below 0.8 at the area of the violet LED (0.78 with HT and 0.7 with RT). Because SOF is a CQ-based composite, it could benefit from the better distribution and penetration of blue light when using the HT, especially in the area of the V LED at the bottom of the specimen. As expected from a bulk-fill composite, SOF obtained a near optimal B/T ratio, despite being a CQ only based composite; also, the manufacturer of SOF recommends a maximum increment thickness of 5 mm, and therefore, a thinner increment like the one used in this study is expected to demonstrate sufficient polymerization. The obtained results of KHN for SOF could be explained because this composite demonstrates better light transmission[24,34] and higher penetrability of blue light.[10,22,25,37]

Surface microhardness measurements of TBF showed higher KHN values on the top surface when the HT was used, near the locations of the blue LEDs. This composite contains CQ, TPO, and Ivocerin photoinitiators, which means that the material may have an improved sensitivity to light emitted by the Polywave LCU, especially at the top surface.[10] That assumption was confirmed by the higher KHN values observed at the top of the specimens when using HT because the greater light distribution could produce greater activation of these photoinitiators. For TBF, the beneficial effect of using an LCU matching the spectral sensitivity of the RBC agreed with the results of other studies[2,3,10,19] because the B/T ratio of TBF was above 0.8 at all the measured locations.

A previous study about depth of cure of bulk-fill composites determined that SOF and TBF had a satisfactory depth of cure when polymerized using a monowave blue LED LCU.[25] That result corroborates the findings of this study, where the depth of cure of both materials was satisfactory at the locations of the blue LEDs. Nonetheless, regarding the effects of beam heterogeneity in bulk-fill composites, results differ from those of another study that considered the effect of beam inhomogeneity in bulk-fill RBCs as "minor."[23] However, the authors of that article extended the time of light exposition by twice the manufacturer's indication and used a high-power setting. In addition, that work did not measure beam profile of the LCU used, nor did it mention the characteristics of the light guide; the increase in the radiant exposure and irradiance delivered to the specimen might have compensated for the nonuniform nature of the light beam.

Comparisons between the results of conventional and bulk-fill composites do not seem to be appropriate because HER and TEC are conventional composites designed to be applied with an incremental technique, while SOF and TBF are bulk-fill composites that can be placed and light cured in 4- to 5-mm increments, and therefore are expected to present a greater depth of cure than conventional composites. Thus, different results from conventional and bulk-fill composites may be attributed to modifications in the composition of the latter to include more efficient photoinitiator systems[24,25] and achieve enhanced light transmission in depth[24] by matching the refractive indexes of filler particles and the resin components to increase depth of cure,[25] as was observed in this study. An appropriate resin formulation may thus enhance reactivity and allow for greater depths of cure,[25] which was confirmed from by the B/T ratio obtained from the KHN measurements.

Spectral emission measurements confirm that both light guides succeed in transmitting and preserving the emission spectrum of the LEDs in the LCU.[1–4,36,38] In the current study, the HT performed better in TBF. Nevertheless, for each of the tested RBCs, the nonhomogeneous beam profile of the Polywave LCU, produced differences in the B/T KHN ratio within the different measurement locations, and therefore in the depth of cure regardless of their photoinitiator composition and the light guide used. This result agrees with other studies that indicate that lack of beam homogeneity might affect polymerization in restorative materials.[5–7,9–12,37] As a consequence, the mechanical properties[12,16,30,32] and clinical performance[5,9,12,25,29] of restorations placed using less than ideal beam homogeneity might be affected even if the top surface of the composite appears to be adequately polymerized.[10,12]

Light-beam heterogeneity is therefore shown to affect the depth of cure of composites by the fact that almost all the tested composites (except for TBF) had a higher B/T ratio in the location of the blue LEDs than in the area of the violet LED. Another important finding was that TEC and TBF showed a higher KHN at the top surface when using the HT, proving that a more homogeneous light beam might be beneficial for the polymerization of superficial composite layers as well.[10] The study results confirm the sensitivity of the microhardness test and the B/T ratio method to detect differences among the surfaces of materials, and it can be described with ease, allowing for a more exact and detailed approach to evaluate depth of cure than other proposed techniques, just as the composite scraping test used in ISO 4049.[10,26,27,30–34]

Regarding the experimental design, microhardness measurements were restricted to locations of the specimens receiving the highest irradiance from the LCU with each light guide tip and would seem to determine if the measured power output and radiant emittance values would be the single factor to influence the KHN results, which was not the case. Future research should consider mapping microhardness of the complete top and bottom surfaces of RBCs and calculating the depth of cure in the regions receiving the lowest irradiance with each light guide type to determine a potential clinical implication produced by the presence of areas receiving very low values of light in the polymerization of restorative composites. Also, for TEC, the less translucent dentin shade used in this study might influence the differences between top and bottom KHN. If enamel or more translucent shades of RBC were used, KHN differences between top and bottom could have been reduced.

## CONCLUSIONS

Within the limitations of the experimental design and based on the findings of the present laboratory study, the following conclusions can be made:

1. In general, within the bulk-fill materials tested, use of a homogenizing tip significantly increased KHN at the bottom of the specimens.
2. Regardless of the light guide type used, the wavelength of the lights affected the KHN of composites. Significantly lower KHN was observed in the areas irradiated by violet light, except for the conventional CQ-based composite (HER) at the bottom when the homogenizing tip was used.
3. Regardless of the light guide type used and the type of photoinitiator contained in the formulation of RBCs, there were significant differences in KHN between the top and bottom surfaces of conventional and bulk-fill RBCs.
4. Using a homogenizing tip did not completely compensate for the nonuniformity of light emitted by a multiwave LCU because power differences were still observed at tip locations correlated with the fixed positions of LED chips present at the proximal tip end. However, the homogenizing tip showed better distribution of emittance than that observed using a conventional light guide, as observed for KHN obtained at the top surfaces of TEC and TBF.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#### 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.

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