Effect of the Inhomogeneity of Curing Light Beam on the Microhardness of Resin Composite with Different Thicknesses and Shades

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Effect of the Inhomogeneity of Curing Light Beam on the Microhardness of Resin Composite with Different Thicknesses and Shades

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A Master Thesis

Submitted to the Department of Dentistry

and the Graduate School of Yonsei University

in partial fulfillment of the

requirements for the degree of

Master of Dental Science

Lan Wang

December 2022

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마지막으로 저의 부모님께서 저에게 해외류학에 대한 이해와 지지를 보내주셔서 감사드립니다. 외국에서 가족처럼 돌봐주신 하숙집 이모 아저씨께 감사드립니다. 동자 선배님, 수잔 선배님, 애니시와 다른 친구들의 도움에 감사를 드립니다. 그들은 공부와 생활 중 나에게 많은 지지를 주었다. 내 옆에서 응원해주고 도와주신 모든 분들께 항상 감사하다는 말을 전하고 싶습니다.

2022 년 12 월 왕란 올림

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ABSTRACT

Effect of the Inhomogeneity of Curing Light Beam on the Microhardness of Resin Composite with Different Thicknesses and Shades

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Purpose. The aim of this study was to evaluate how the inhomogeneity of polymerization with monowave light-curing unit (LCU) affected the microhardness of resin-based composite (RBC) restorations with different thicknesses and shades.

Methods. Four body shades (A1B, A2B, A3B, A4B), one dentin shade (A3D), and one enamel shade (A3E) of a nanofill composite resin (Filtek Z350) were selected. Teflon discs were cut using a blade into four thicknesses: 1, 2, 3 and 4 mm with holes 10mm in diameter drilled in the center. The hole was filled with Filtek Z350 and irradiated in bulk using Elipar DeepCure-S for 40 seconds. The spectral distributions were obtained using a spectrometer (USB 4000). Hardness values were measured after 7-day storage at 37°C. The irradiance data were statistically analyzed using a one-way analysis of variance (ANOVA) followed by Tukey honest significant difference (HSD) tests. 1-way ANOVA with the Tukey HSD test was used to analyze the effect of thicknesses and shades on the RBC's microhardness (*P*=.05). Repeated measured 1-way ANOVA with the Least Significant Difference (LSD) test was used to analyze the effect of measuring points on the RBC's microhardness (*P*=.05). Pearson's correlation was used to correlate the irradiance and microhardness of RBC at each measuring position (*P*=.05).

Results. The irradiance values decreased significantly with increased specimen thicknesses and with the opacity and intensity of the shades increased (*P*<.05). The microhardness decreased as specimen thickness increased (*P*<.05). The microhardness tended to decrease from the center to the periphery, and this tendency was more evident in the thick (3- and 4-mm) specimen and in dark (A3B and A4B) and opaque shade (A3D) RBC (*P*<.05). Pearson correlation test revealed a positive exponential correlation between the irradiance of the RBC specimens and microhardness in all the measuring positions.

Conclusion. Light transmission of RBC decreased with the increasing specimen thicknesses and with the intensity and opacity of the shades increased.

LCU using inhomogeneous light output can have different effects on the RBC depending on the thicknesses and shades. In the 1-mm thickness case, the microhardness of the RBC performed homogeneous distribution, while in thickness of 2mm or more, the RBC showed inhomogeneous microhardness.

Keyword: dental curing lights; resin composite; inhomogeneous; irradiance; microhardness

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I. Introduction

Direct Resin-based composite (RBC) restorations have been widely used in restorative dentistry procedures. RBC goes from a plastic phase to a semisolid phase through a process called polymerization. The start of this process involves reactions that produce free radicals. These free radicals can be the result of energy (heat or light) or chemical activation. The clinical success of composite resins is influenced by the polymerization process. Many factors affect the degree of polymerization of RBCs, including the shade,[1] increment thickness, cavity diameter, cavity location,[2] light unit system used,[3] light intensity, exposure duration,[4] light curing tip distance from the curing RBC surface, substrate through which the light is cured (e.g., curing through ceramic, enamel, or dentin), filler type and temperature.[4]

To ensure optimal photo-polymerization of the RBC, the radiant exposure and spectral range requirements of the RBC must be fulfilled by the radiant output from the light-curing unit, while avoiding damage to the oral tissues caused by excessive temperature increases.[5]

The most commonly used photosensitizer in RBCs is camphorquinone (CQ). However, CQ is a photoinitiator that has a color limitation, so some manufacturers started using resin compositions that contained alternative photoinitiators that rendered less yellow color in the resin such as 2,4,6-trimethylbenzoyldiphenylphosphine oxide (TPO), 1-phenyl-1,2-propanedione (PPD), or the germanium based initiator, Ivocerin to reduce the CQ concentration[6]. De Oliveira et al. stated that compounds containing only CQ or TPO demonstrated homogeneous healing profiles, with a similar degree of conversion (DC) at depths of 1, 2, and 3mm.[7] Therefore, the inclusion of a high concentration of CQ in RBC is beneficial to increasing the degree and homogeneity of polymerization.

In order for the photoinitiator to be activated, it must be subjected to light from a source. The light-emitting diode (LED) light-curing unit (LCU) is considered to be the gold standard for the source in contemporary dentistry.[8] Each generation of

LED LCU emits its irradiance power and wavelength spectrum, which should match the light absorption spectrum of photoinitiators in resin-based materials. The first- and second-generation LEDs that utilized the same monowave technology (single-peak), emitted only blue light above 420 nm could only activate the CQ component within these resins and were unable to light-cure restorative materials using photoinitiators of shorter wavelength. To overcome this limitation, third-generation, polywave blue-violet LED-based LCUs were introduced. By incorporating different LED color chips into the curing light, the lights now emitted both the lower wavelengths of violet light, usually from 390 to 430 nm, as well as light from 440 to 500 nm, and could now activate all the different photoinitiators used in a dental resin.[9] However, the introduction of new wavelength outputs further compounds the inhomogeneity of irradiance and power of the light beam.[5,10] Other than polywave, monowave LCUs have LED chips that all output at approximately the same wavelength.[5,9] Even so, the light beam from the LCU has an inhomogeneous irradiance and power output. A previous study stated that in RBC containing CQ and TPO, the polywave LCUs showed better performance in the conversion of monomer to polymer, in addition to higher Knoop microhardness, when compared to the LCU monowave.[11] However, in RBC that contains only CQ, monowave LCU performed better than polywave with greater irradiance and more energy.[11]

Differences in the light outputs among LCUs are often detectable by a "dental radiometer". The International Organization for Standardization (ISO) 6050 standard for calculating the radiant exitance (irradiance) assumes that the emitted power and spectral emission profiles are homogeneously distributed across the light tip end and can be fully characterized by the use of a single value. Similarly, both the ISO 11405 bond strength test and the ISO 4049 depth of cure evaluation assume that LCU output is uniformly distributed across the emitting end of the light tip and that the target specimen will receive the same irradiance and wavelengths of light across its entire surface.[12] However, studies had established that numerous dental LCUs have emitting tips that are rarely radially symmetrical and are highly inhomogeneous.[13] Therefore, the commonly used averaged irradiance and spectral emission across an LCU cannot fully describe the result the light output has on resin polymerization, and the relative interactions of these inhomogeneous light outputs at specific locations across resin surfaces should be considered.

Surface microhardness using Vickers indenters is a reliable and commonly-used method to test how well a resin is cured. The Vickers microhardness test is one of the best methods for testing the hardness of resin composites.[14] The majority of previous studies that made multiple microhardness measurements on RBC with different shades and thicknesses took only a few microhardness readings at the center of the sample, where the specimen may be the most cured.[1,2,15-17]

The existing evidence mainly reports findings on the correlation between the heterogeneity of emitted light and the microhardness of RBCs.[5,18,19] Go et al reported the effects of LCU's inhomogeneous beam profile on the composites with different thicknesses and types.[20] However, studies that provide detailed hardness data on the impact of beam inhomogeneity as the opacity and shade of RBC vary are still lacking.

The present study was performed with the purpose of evaluating how the inhomogeneity of polymerization with monowave LCU affected the microhardness of RBC with different thicknesses and shades. The null hypothesis tested was as follows:

(1) There was no significant difference in the irradiance between different thicknesses and shades of RBC;

(2) There was no significant difference in the microhardness between different thicknesses of RBC;

(3) There was no significant difference in the microhardness between different shades of RBC;

(4) There was no significant difference in the microhardness between different measuring positions on the surface of RBC.

II. Materials and Methods

1. Material Preparation

Four different body shades, one dentin and one enamel shade of a nanofill composite resin (Filtek™ Z350, 3M-ESPE, St. Paul, MN, USA) were selected: two shades at the extremes of the body shade guide, A1B (lightest) and A4B (darkest), two in the middle of the body shade guide (A2B and A3B) and A3D and A3E as a control group.

Elipar DeepCure-S (LED, 3M-ESPE, St Paul, MN, USA) with a 9mm functional diameter of the light guide, was used for this study. The radiant power of the light was measured with a spectrometer (USB4000; Ocean Optics, Dunedin, FL, USA) connected with an Integration sphere (Labsphere, Ocean Optics, Dunedin, FL, USA) with a Ø3.9-mm fiber-optic. The radiant emittance, corrected by the diameter of the curing tip, was 1, 372 mW/cm^2.

Teflon discs were cut using a blade into four thicknesses: 1, 2, 3, and 4mm with holes 10mm in diameter drilled in the center. The discs were smoothed using 600- and 1200-grit silicon carbide sandpaper and their thicknesses were confirmed with a digital caliper (precision, ±0.1 mm; Mitutoyo Digimatic Calipers, Tokyo, Japan). Composite samples were packed into the holes in the Teflon molds and leveled using a 1-mm thick glass plate (Fig 1). After the placement of the material was complete, the mold was immediately placed over the light-curing unit's tip and the composite was photocured for 40 s using the conventional curing mode.

Ten specimens of each shade and thickness were fabricated with the dimensions of the Teflon mold, and a total of 240 specimens were produced.

For the 4-mm thick A3D shade specimens, the bottom surfaces were not adequately polymerized after the 40s of light curing. The measurement was taken after the soft part of the RBC was scraped away with a blade. The final thickness of the specimens was 3.3mm.

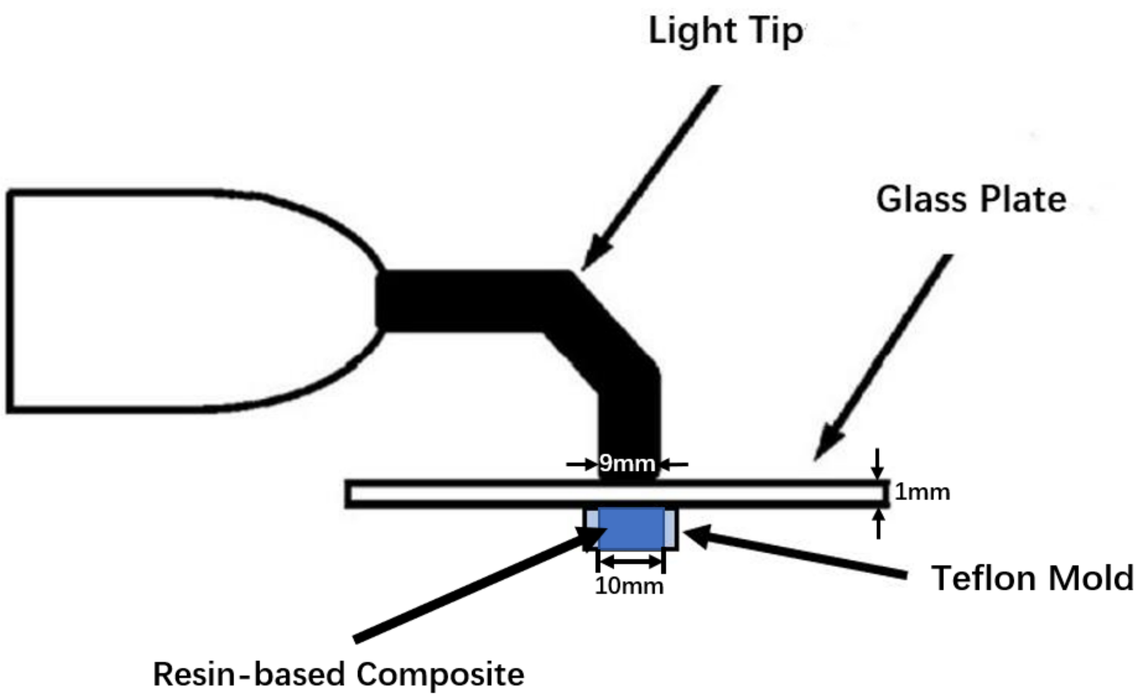

Figure 1. Set up of the light curing condition.

2. Curing light's Beam Profile Measurement

Irradiance distribution of curing light was measured using a Laser Beam Profiler (Model: BGS-LT665, Ophir Spiricon, Logan, UT, USA) and a CCTV Lens (25mm focal length, Ophir Optronics, Jerusalem, Israel) with the diaphragm aperture of f/4. The LCUs were placed directly on a neutral-density (ND) Filter with a 4.0 optical density (OD) value (Edmund Optics, Barrington, NJ, USA) and holographic diffuser (Diffusing angle 60°, Edmund Optics, Barrington, NJ, USA), in front of the camera lens. (Fig. 2)

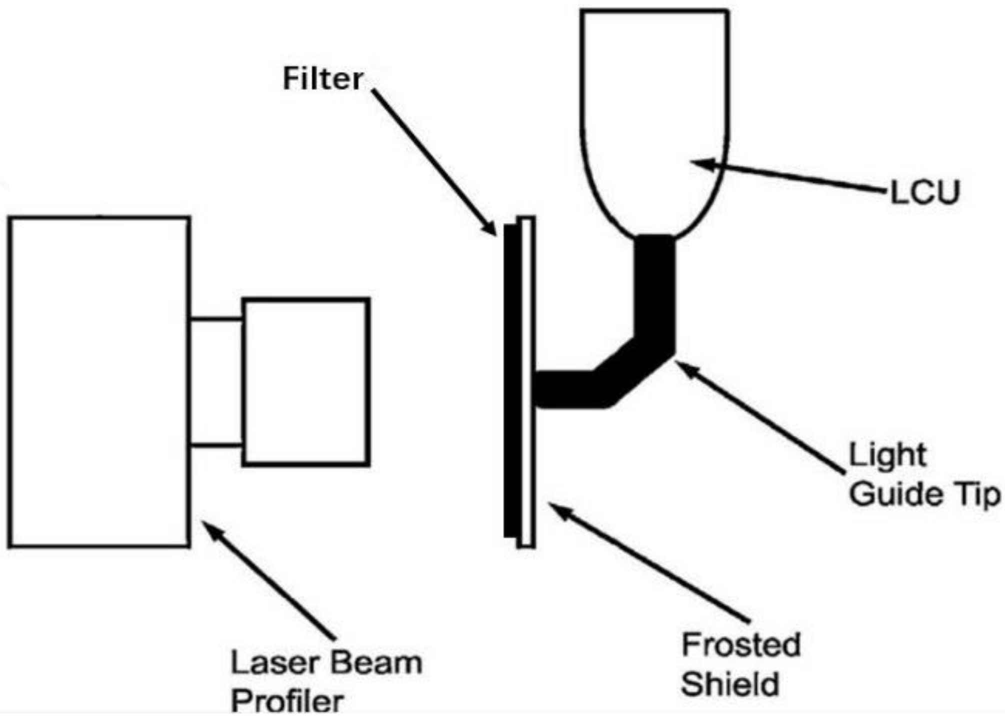

Figure 2. Schematic experimental setup of the beam profiler measurement.

3. Measurement of irradiance after passing through composites

The composite specimens were stored dry at 37ºC for seven days after light curing. Five specimens from each group were randomly selected and used for the irradiance measurement. Each specimen was attached to the curing light's tip with black adhesive paper and the curing light is activated.

The irradiance of light passing through the composite specimen was measured with a cosine corrector (CC-3-UV-S, Ocean Optics, Dunedin, FL, USA) attached to a spectrometer (Flame-S, Ocean Optics, Dunedin, FL, USA). The irradiance (mW/cm^2) was calculated by dividing the diameter of the Ø3.9-mm optical fiber.

4. Vickers Hardness Test

After the photoactivation procedure, five specimens of each group were stored dry at 37ºC for seven days. After that, the bottom surfaces were ground with #600-grit SiC abrasive to obtain polished, flat surfaces.

Indentations for Vickers hardness number (VHN) measurements were sequentially performed in a hardness testing machine (MMT-X, Matsuzawa, Akita, Japan). Three readings were taken on the bottom surfaces under a load of 980.7mN for 10 s each, using an objective of 40 X. One indentation is in the center, and the other two are on a radius of 3 mm outside (Figure 3).

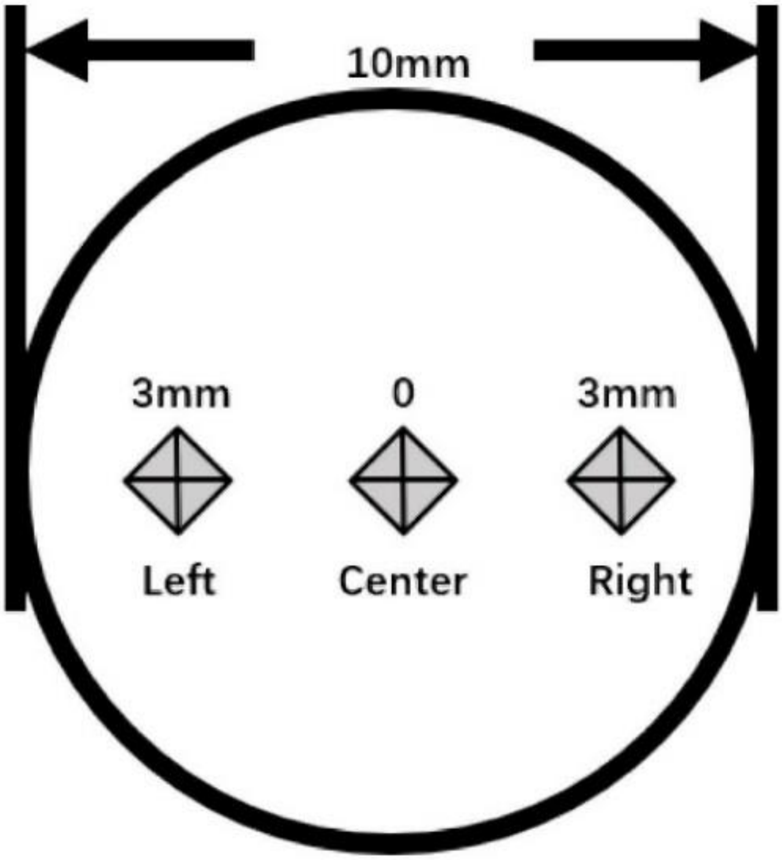

Figure 3. Size of the specimen and the microhardness measurement points.

5. Statistical Analysis

The effect of the shades and thicknesses of the RBC on irradiance was statistically analyzed (IBM SPSS Statistics V26.0, IBM Corporation, Armonk, NY, USA) using a one-way analysis of variance (ANOVA) and Tukey honest significant difference (HSD) tests (*P*=.05). The analyzing factors were specimen thickness and composite shade.

The effect of thicknesses and shades on the RBC's microhardness was analyzed with 1-way ANOVA followed by the Tukey HSD test (*P*=.05). Repeated measured 1-way ANOVA with the Least Significant Difference (LSD) test was used to analyze the effect of measuring points on the RBC's microhardness (*P*=.05).

Pearson's correlation was used to correlate the irradiance (mW/cm^2) and microhardness (Hv) of RBC at each measuring position (*P*=.05)

III. Results

1. Curing light's Beam Profile Measurement

Representative beam profiles of the Elipar DeepCure-S shown in Figure 4 illustrate the inhomogeneous irradiance distribution across the light tip. With a 9mm functional diameter of the light guide, an average irradiance value across the light tip was calculated to be 1, 372mW/cm^2. The majority of its light output was concentrated in a circular area about 6 mm in diameter located near the center of the light tip. The energy decreased toward the periphery. The irradiance peaks were associated with the LED chip locations or the reflections from the reflectors within the body of the LCU.

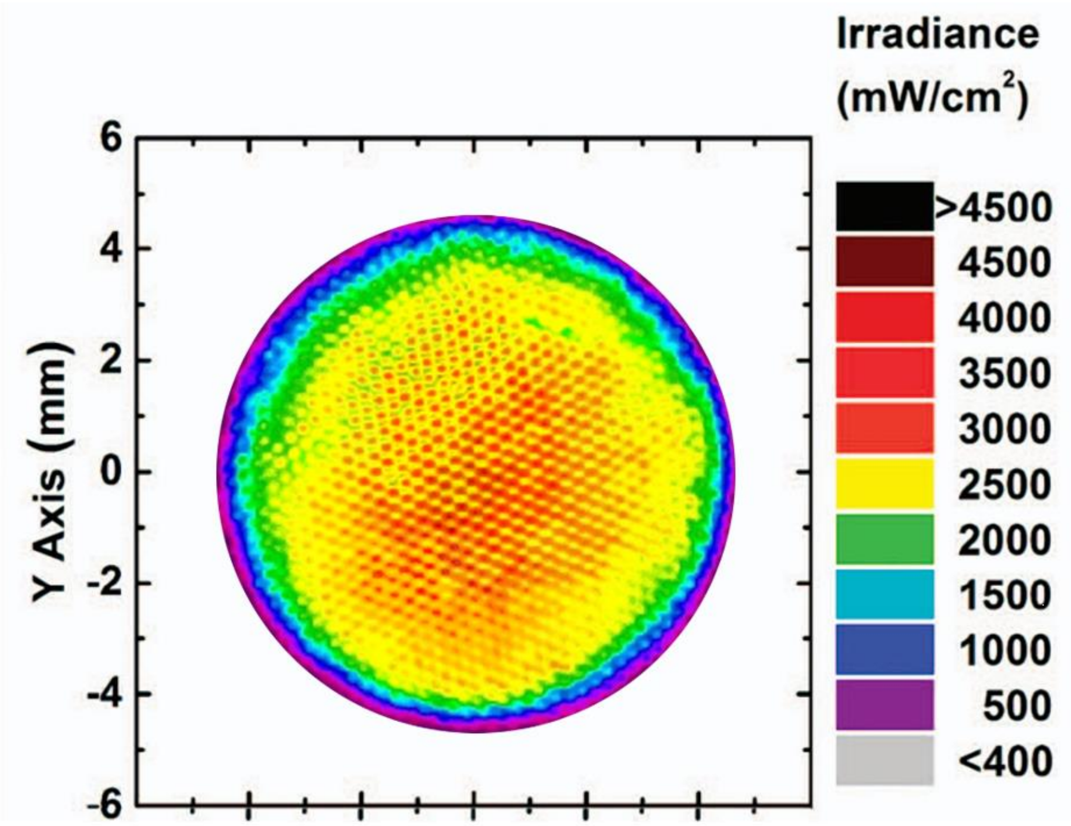

Figure 4. Representative beam profile images of curing light (Elipar DeepCure-S). A holographic diffuser and a 4.0 optical density (OD) filter are used to attenuate lights to the dynamic range of the charge coupled device (CCD) camera with an aperture of f/4.

2. Measurement of irradiance after passing through composites

The values of shade and thickness were submitted to one-way ANOVA (P =.000). Considering each factor independently, Table 1 presents the significant differences among the different shades (P <.001, 1-way ANOVA) and thicknesses (P <.001, 1-way ANOVA).

In the Tukey post hoc test, the irradiance values of different specimen thicknesses were ranked 1-mm>2-mm>3-mm>4-mm (Table 1), except for the A3D shade group that there were statistically similar results between 3- and 4-mm specimens (P= .971, Tukey post hoc test). The irradiance values decreased significantly with increased specimen thicknesses (Fig 5).

Tukey post hoc test results among different composite shades in the same opacity were ranked A1B>A3E>A2B>A3B>A4B>A3D (Table 1). For the same opacity, the irradiance values decreased significantly with greater intensity of the shade while for the same intensity, the irradiance values decreased significantly with greater opacity (Fig 6).

Light transmission decreased significantly with more opaque and darker RBC shades and increased RBC thicknesses.

Table 1. Mean and standard deviation of irradiance (mW/cm²) of Filtek Z350 specimens after 7-day storage with statistical summaries.

	A1B	A2B	A3B	A4B	A3D	A3E	df	F	p
1mm	203 ± 14.0^{Aa}	171 ± 11.1^{Ab}	144 ± 12.6^{Ac}	121 ± 11.4^{Ad}	57 ± 8.5^{Ae}	171 ± 11.5^{Ab}	29	204.91	<.001
2mm	98 ± 5.7^{Ba}	73 ± 8.7^{Bc}	55 ± 8.2^{Bd}	36 ± 4.9^{Be}	15 ± 3.3^{Bf}	90 ± 8.8^{Bb}	29	370.04	<.001
3mm	36 ± 4.4^{Ca}	29 ± 7.5^{Cb}	23 ± 8.2^{Cc}	11 ± 4.3^{Cd}	2 ± 0.7^{Ce}	34 ± 5.1^{Ca}	29	195.02	<.001
4mm	17 ± 1.4^{Da}	12 ± 4.0^{Db}	8 ± 1.3^{Dc}	3 ± 1.1^{Dd}	1 ± 0.3^{Ce} *	16 ± 2.1^{Da}	29	409.85	<.001
df	19	19	19	19	19	19			
F	790.84	1935.24	4666.60	3459.46	320.38	512.45			
p	<.001	<.001	<.001	<.001	<.001	<.001			

Different uppercase superscript letters represent statistical differences within columns (thickness) and different lowercase superscript letters represent statistical differences within rows (shade) (P<.05). *In the 4-mm A3D group, the measurement was taken with a thickness of 3.3mm.

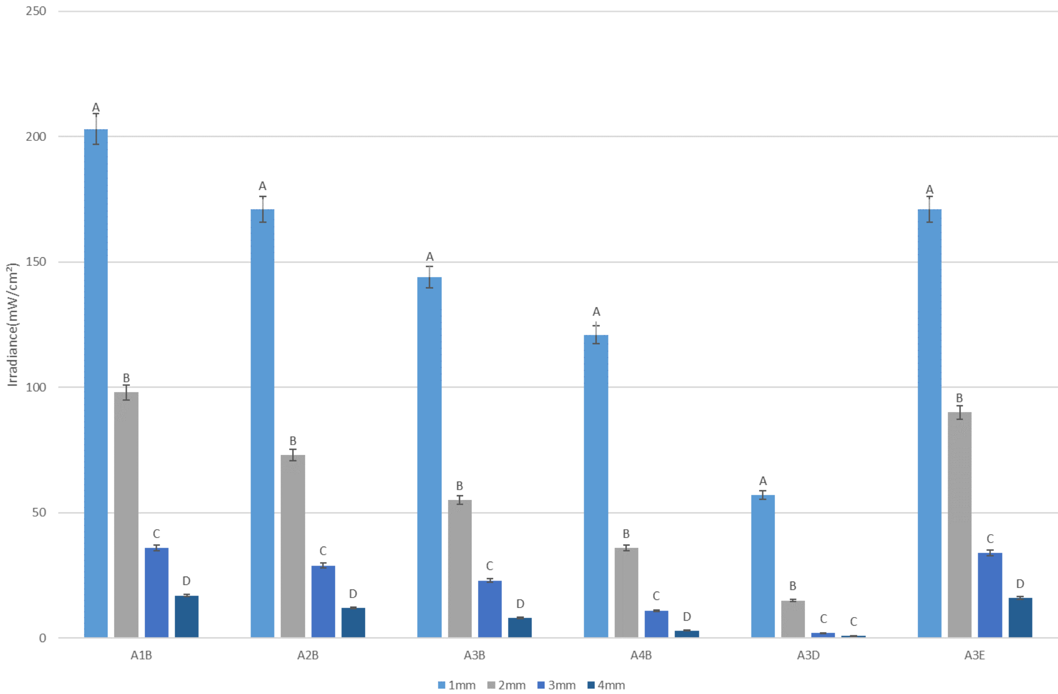

Figure 5. Comparison of mean irradiance (mW/cm^2) of different composite thicknesses in each shade (P<.05). Different uppercase superscript letters represent statistical differences within thicknesses.

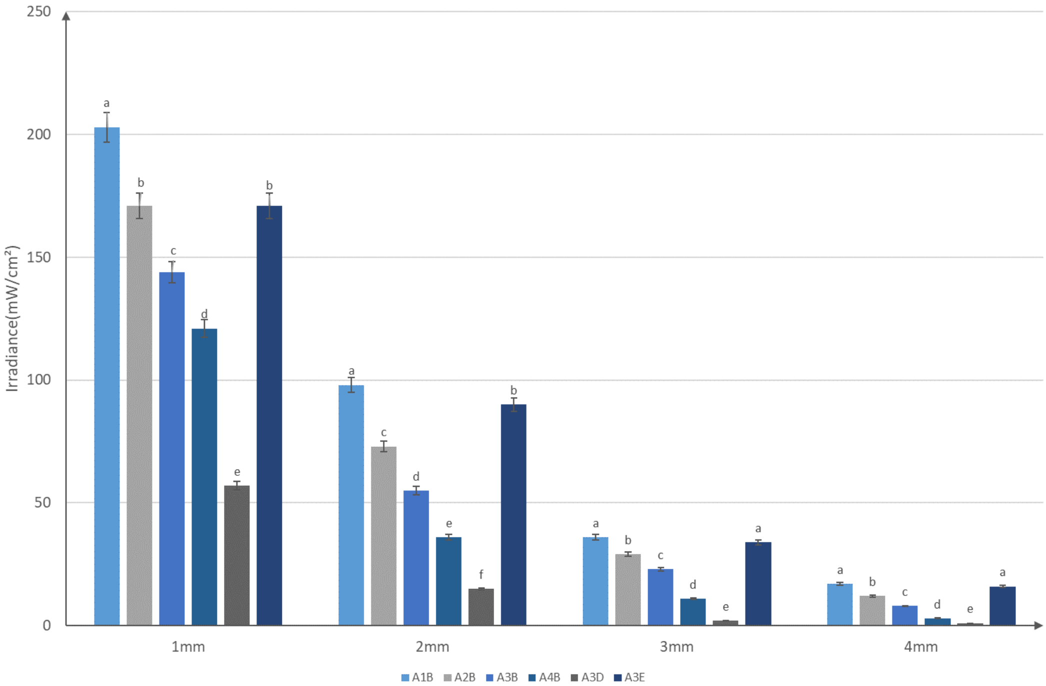

Figure 6. Comparison of mean irradiance (mW/cm^2) of different resin shades in each thickness (P<.05). Different lowercase superscript letters represent statistical differences within shades.

3. Vickers hardness test

The means and standard deviations of microhardness values are summarized in Table 2. In each shade group, 1-way ANOVA test results showed significant differences (*P*<.05) among the specimen thickness groups in the same measuring position. From the Tukey post hoc test, the microhardness was 1 mm, 2 mm>3 mm>4mm in most cases. However, in A4B and A3D (left position), A3D (center position), and A4B (right position), the microhardness values in 1-mm thick groups were significantly higher than that in 2-mm thick groups (*P*<.05). (Table 2 and Fig. 7)

The 1-way ANOVA revealed that the shades of RBC had statistically significant effects on microhardness in all the measuring positions of all thicknesses (*P*<.05). The Tukey post hoc test showed that in 1- and 2-mm thick groups, there was no significant difference between shades (*P*>.05) except A3D shade groups, in which the microhardness was significantly lower than other shade (*P*<.05). In the 3- and 4-mm thickness, the microhardness was lowest in A3D, followed by A4B. The microhardness in A1B was highest in all position (*P*<.05). (Table 2 and Fig. 8)

Repeated measured 1-way ANOVA results showed the significant effects of the measuring positions on the microhardness of RBC in 2-, 3- and 4-mm thick groups (*P*<.05). The microhardness tended to decrease from the center to the periphery of the RBC surface (*P*<.05). This tendency was larger when the thickness of the specimen was thicker (3mm, 4mm), and appeared more clearly when the RBC shade was darker (A3B, A4B) or opaquer (A3D). At the 1-mm thickness, the microhardness showed a uniform distribution on all the measuring positions

(P>.05), except in the 1-mm A3D group (P<.05). (Table 2 and Fig. 9 and 10)

Table 2. Mean and standard deviation of bottom microhardness (Hv) of Filtek Z350 specimens after 7-day storage with statistical summaries.

Shade	Position	1mm	2mm	3mm	4mm
A1B	left	77.8±1.7^{Aa}	76.6±1.3^{Aa}	73.9±0.7^{Bb}	65.0±1.1^{Cb}
	center	78.9±0.7^{Aa}	77.1±0.6^{Ba}	76.4±0.7^{Ba}	70.3±1.5^{Ca}
	right	78.4±1.4^{Aa}	76.7±1.0^{Aa}	74.1±0.4^{Bb}	64.7±1.5^{Cb}
A2B	left	77.2±0.8^{Aa}	76.1±0.8^{Ab}	69.7±0.9^{Bb}	60.0±1.4^{Cb}
	center	77.8±0.6^{Aa}	77.8±0.6^{Aa}	74.0±1.0^{Ba}	64.3±0.7^{Ca}
	right	76.7±2.1^{Aa}	76.9±0.3^{Aab}	70.9±1.7^{Bb}	60.4±1.3^{Cb}
A3B	left	77.6±1.0^{Aa}	75.8±1.0^{Aa}	67.3±1.4^{Bb}	57.8±1.8^{Cb}
	center	78.8±0.3^{Aa}	77.2±0.8^{Aa}	72.0±1.3^{Ba}	66.4±1.2^{Ca}
	right	77.4±1.5^{Aa}	75.5±1.8^{Aa}	67.0±0.8^{Bb}	57.7±1.4^{Cb}
A4B	left	77.5±0.9^{Aa}	74.6±1.6^{Bb}	40.6±1.7^{Cb}	35.7±1.7^{Db}
	center	78.9±1.0^{Aa}	76.8±0.4^{Aa}	58.0±2.3^{Ba}	46.2±0.7^{Ca}
	right	78.0±1.2^{Aa}	74.3±1.4^{Bb}	40.0±1.0^{Cb}	35.5±1.4^{Db}
A3D	left	75.0±0.9^{Ab}	65.3±1.2^{Bb}	23.8±1.8^{Cb}	16.6±2.0^{Db} *
	center	77.1±1.4^{Aa}	71.3±0.8^{Ba}	32.6±1.5^{Ca}	24.1±1.4^{Da} *
	right	75.5±1.1^{Aab}	65.6±0.7^{Bb}	22.2±1.2^{Cb}	15.7±1.2^{Db} *
A3E	left	75.9±1.0^{Ab}	75.1±1.2^{Ab}	69.6±0.6^{Bb}	66.0±1.9^{Cb}
	center	77.7±0.6^{Aa}	77.0±0.3^{Aa}	74.6±0.7^{Ba}	72.1±1.3^{Ca}
	right	76.3±0.8^{Ab}	75.1±0.6^{Ab}	69.1±0.6^{Bb}	64.9±2.4^{Cb}

Capital letters in a row represent statistical differences between thicknesses in each measuring position of each shade (P<.05); Small letters in a column represent statistical differences among measuring positions in each shade of each thickness (P<.05). *In the 4-mm A3D group, the measurement was taken with a thickness of 3.3mm.

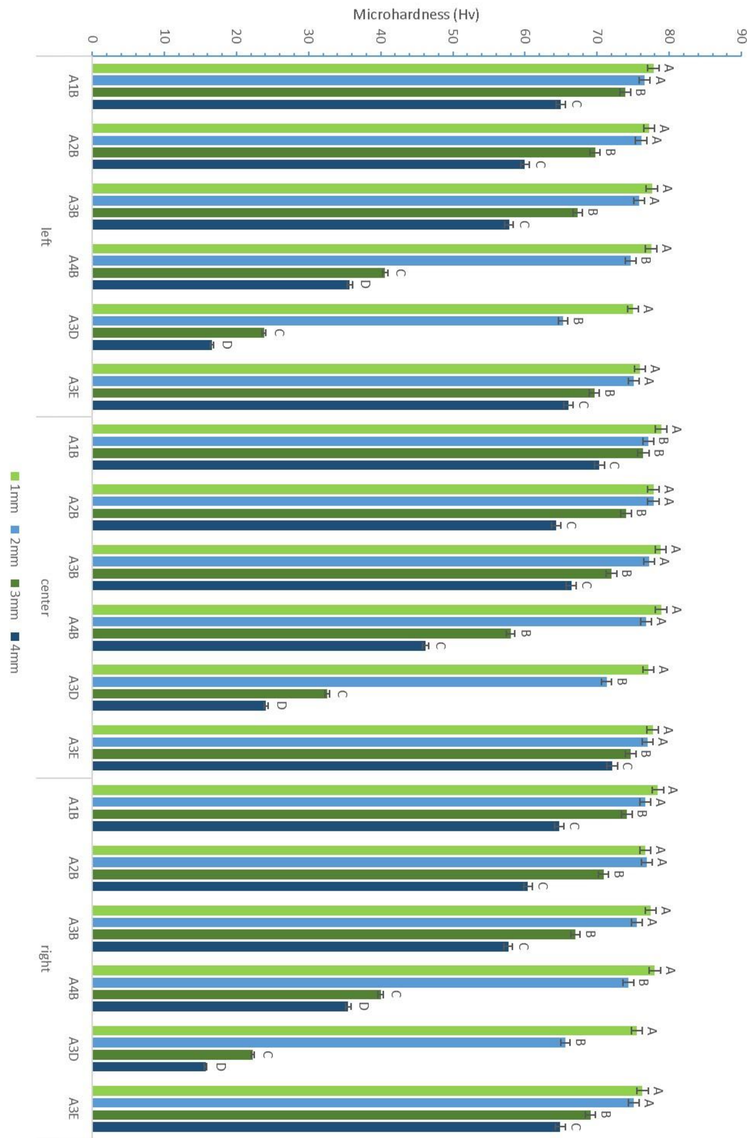

Figure 7. Comparison of Mean bottom microhardness (Hv) between different thicknesses in each measuring position of each shade of Filtek Z350 irradiated for 40s (*P*<.05). Different uppercase superscript letters represent statistical differences within thicknesses.

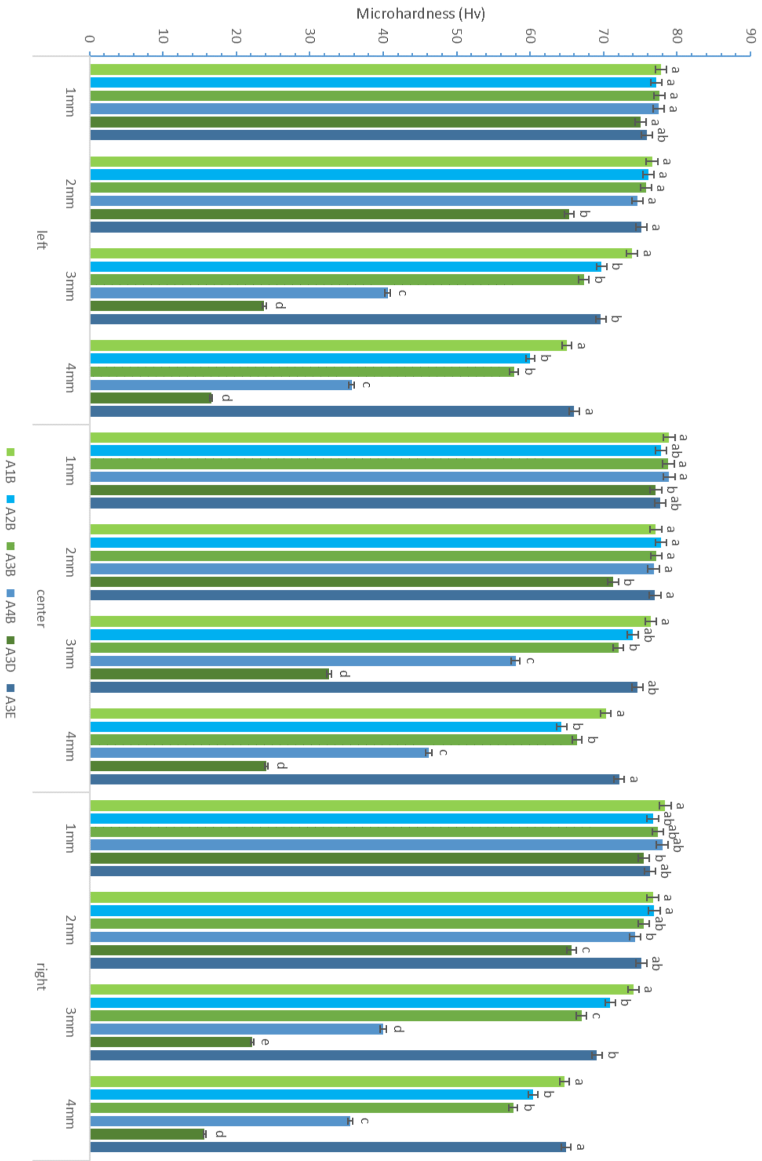

Figure 8. Comparison of Mean bottom microhardness (Hv) between different shades in each measuring position of each thickness of Filtek Z350 irradiated for 40s (P<.05). Different lowercase superscript letters represent statistical differences within shades.

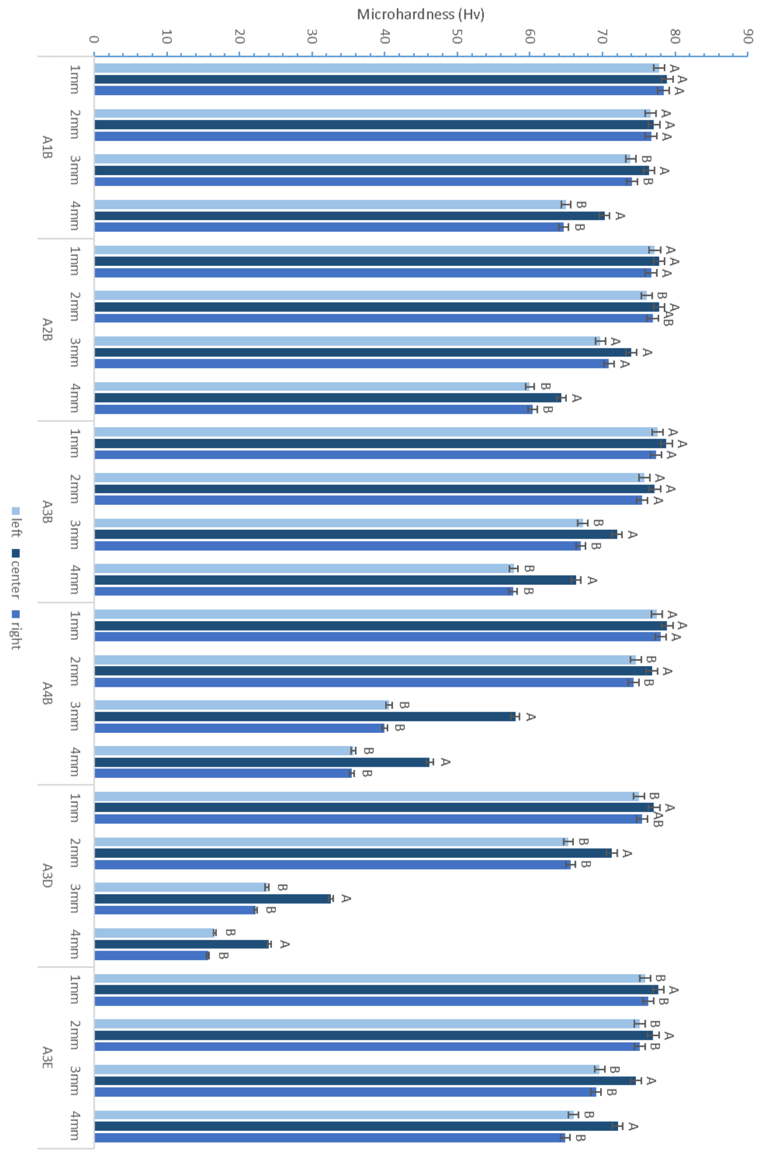

Figure 9. Comparison of Mean bottom microhardness (Hv) between different measuring positions in each thickness within each shade of Filtek Z350 irradiated for 40s ($P<.05$). Different uppercase superscript letters represent statistical differences within measuring positions.

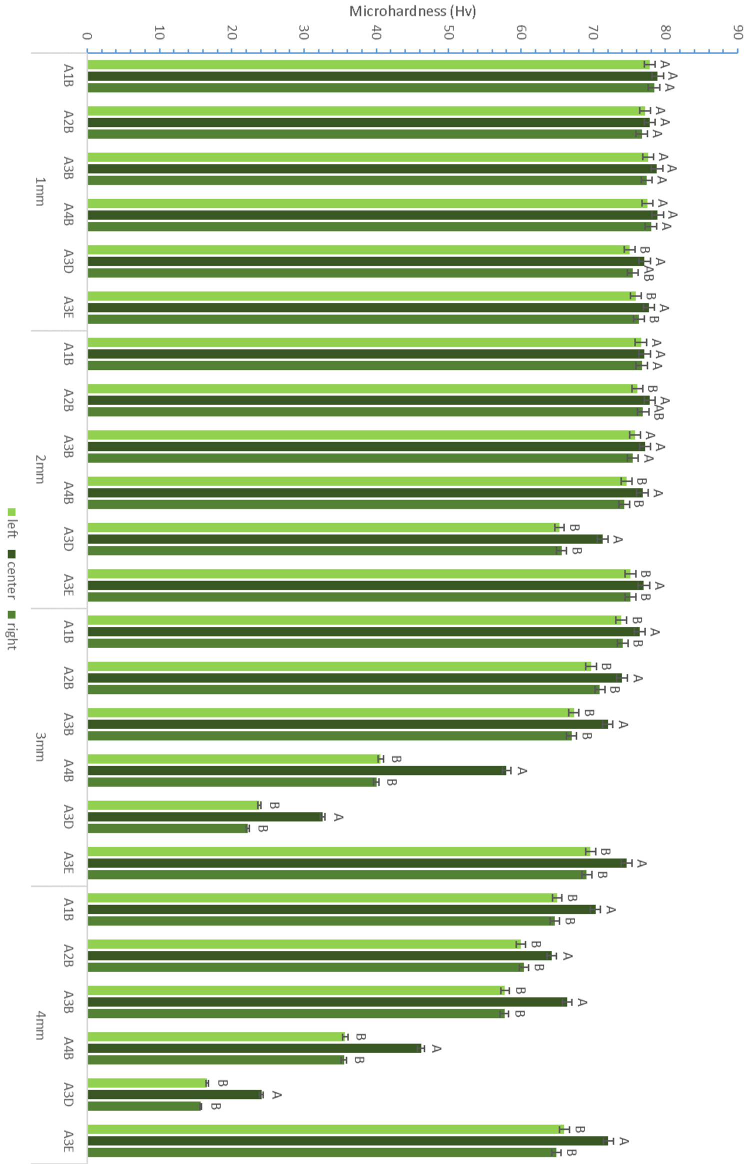

Figure 10. Comparison of Mean bottom microhardness (Hv) between different measuring positions in each shade within each thickness of Filtek Z350 irradiated for 40s (*P*<.05). Different uppercase superscript letters represent statistical differences within measuring positions.

4. Correlation between irradiance and microhardness

In accordance with the Pearson correlation test, there were positive exponential correlations between the irradiances of the RBC specimens and microhardness values in the measuring point left (r=0.60, P<.001), center (r=0.54, P<.001) and right (r=0.60, P<.001) (Fig. 11).

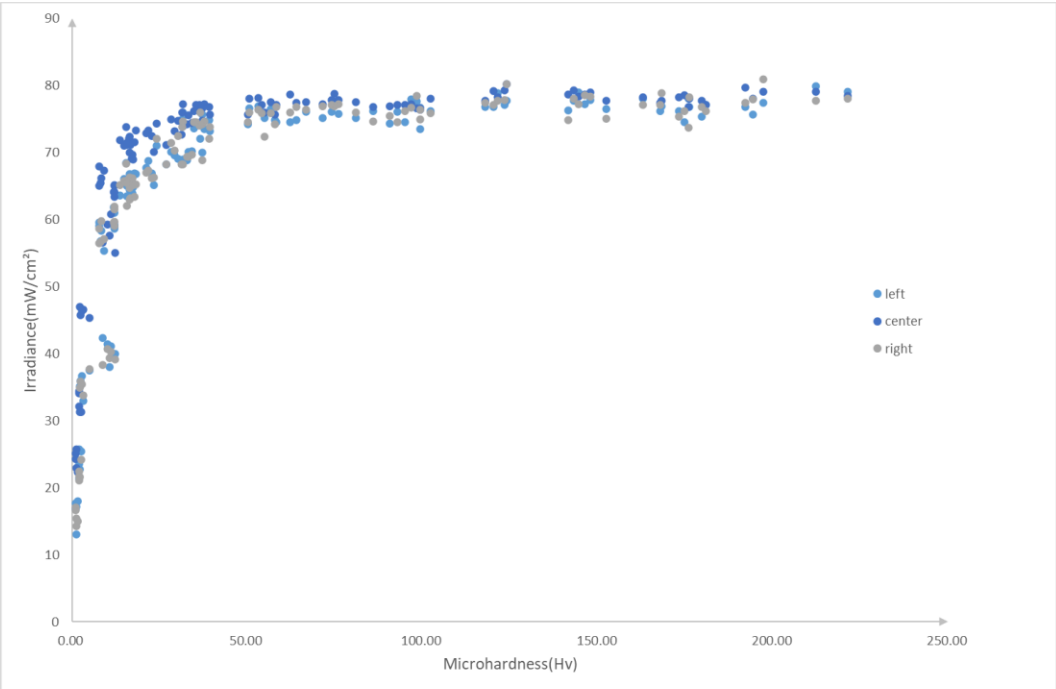

Figure 11. Correlation between the irradiance(mW/cm²) and microhardness (Hv).

IV. Discussion

The present study evaluated the effect of the inhomogeneity of monowave LED curing light beam on the microhardness of cured RBCs with different thicknesses and shades, through irradiance measurement and the Vickers hardness test.

The irradiance decreased significantly with increased specimen thicknesses, except no significant differences were found between 3- and 4-mm A3D groups. Increasing shade intensity led to a significant decrease in irradiance for the same opacity, while increased opacity resulted in a significant decrease in irradiance for the same intensity. (Table 1 and Fig. 5 and 6) Therefore, the first null hypothesis was rejected.

In the case of the highest opacity shade (A3D) 4-mm thick group, the final thickness of the specimens was 3.3mm because the bottom surfaces of the specimens were not adequately polymerized after a fixed duration of 40 seconds of light curing, which may affect the result. The irradiance declined sharply between 1- and 2-mm specimens, which agreed with previous studies that energy loss in the first 1 mm was notably higher than in the 2-mm specimens, and irradiance in the 4-mm blocks was statistically significantly impacted by the block thickness.[21,22] According to previous studies, the inner compositions and structures of the examined materials affected the transmitted light irradiance.[23] Light transmission through resin composite comprised of diffuse and straight-line transmissions, resulting from light scattering at the surface of the filler particles and matrices. As the thickness of the resin composite increases, more scattering and refraction within the material could occur.[23-25]

The shade of composite material is affected by filler shape, filler particle size and filler content.[26] An organic matrix reduction may be seen in the area between the particles' interfaces as a result of the increased filler content with increased opacity and intensity of the shade. Due to the fillers' proximity, reduced light intensity reaches the photoinitiator.[27] Therefore, as the opacity and intensity of the shade increased, light transmission considerably decreased.

The microhardness decreased as specimen thickness increased from 2-mm thickness, with the exception of A3D and A3B shades, where the microhardness declined from 1-mm thickness. (Table 2 and Fig. 7) Based on these results, the second null hypothesis was partially rejected. The result in the present study was consistent with previous studies that reported that between 1 mm and 1.5 mm, no discernible difference in the microhardness was found, and specimens with thicknesses of 3 mm or more failed to demonstrate adequate polymerization.[20,22] This may be attributed to the fact that light intensity was significantly diminished while passing the bulk of the RBC due to light scattering and absorptions, which affected the polymerization efficiency. The RBC was not adequately polymerized beyond 3mm depth in the highest opacity shade (A3D) group in the present study, this fact compromises the success of the restorative treatment with packable composite when used as a bulk technique because the existence of unpolymerized resin in the bulk of the restoration may have deleterious effects, increasing the risk of secondary caries underneath the material, hypersensitivity, discoloration or even fracture of the restoration.[28] It illustrates that using the manufacturer’s recommended exposure time of 40s may be insufficient to polymerize the entire RBC specimen. the tip diameter and the homogeneity of the light emitted from the LCUs affected the results.

There were no meaningful differences between the shades in the 1- and 2-mm thickness cases, with the exception of the A3D shade groups, where the microhardness was noticeably lower. On contrary, as the intensity and opacity of the shades increased in the 3- and 4-mm thickness cases, the microhardness decreased. (Table 2 and Fig. 8) The third null hypothesis was partially rejected. Approximately, Thome et al. reported that lighter-colored resins showed higher microhardness values compared to dark-colored ones that require more lighting time to achieve higher hardness values.[29] Darker shades exhibit a lower degree of polymerization, resulting in lower mean hardness values.[30] The intensity of the shade among the materials was affected by the light scattering behavior caused by the filler shape.[26] The opacity of the material was influenced by the filler amount and the difference in the refractive indices between the filler particles and the resin matrix.[31] Due to the increasing intensity and opacity of shades, the light transmission was diminished when passing through them. The photopolymerization initiation rate depends on the incident light intensity, so the increased intensity and opacity of shade led to a decrease in microhardness.

The fourth null hypothesis was also partially rejected. The RBC for the 2- to 4-mm thickness cases displayed an inhomogeneous distribution of the microhardness that declined from the center to the periphery apart from the 2-mm A1B group and the RBC's microhardness distribution was homogeneous in the 1-mm thickness case excluding the 1-mm A3D group. (Table 2 and Fig. 9 and 10) The result expounded the effects of light output inhomogeneity on surface microhardness, which agreed with the previous study that the light passing through 2- and 4-mm thick materials showed an inhomogeneous distribution.[22] The highest opacity shade performed inhomogeneous distribution and the lowest intensity showed a more homogeneous distribution of microhardness in the present study. (Table 2 and Fig. 9 and 10) As the increasing thickness, opacity and intensity of shade, the total amount of light that reached the bottom was significantly diminished due to the absorption, refraction and scattering of light. The total amount of light that reached the bottom of the 4-mm thick specimens was only about 10% of the light that was delivered to the top.[25] The regions of increased polymerization caused by localized regions of power concentration across a light beam were becoming obvious and the periphery areas were inadequately polymerized.[32]

The irradiance showed an exponential correlation with the microhardness in all the measuring points. (Fig. 11) This was in conformity with previous studies that illustrated that the radiant power measured at each hardness point and the microhardness had a positive linear correlation. In addition, due to the exponential nature of the link between radiation exposure (dose) and polymerization, this correlation was exponential (or linear in a semi-log scale).[25] The correlation at left and right was higher than that at the center in all shades and thicknesses. (r=0.60 at the left point, r=0.60 at the right point, r=0.54 at the center point) It might explain why the differences between the center and the peripheries were greater with the increase of specimen thickness and the increase of opacity and intensity of the RBC shade (Fig. 9 and 10), which stated a highly significant correlation between the locations of maximum microhardness and locations of irradiance maximum LED chips.

With a 9mm functional diameter of the light guide, an average irradiance value across the light tip was calculated to be 1, 372mW/cm^2. This value agrees with the manufacturer's stated average irradiance value of 1, 470mW/cm^2. The image of the LCU tip end has shown that the LCU delivered extremely high output levels near the center of the light tip and the energy decreased toward the periphery, which informs the inhomogeneous irradiance distribution across the light tip. As per previous reports that it is common for LCUs to have beam profiles with hot spots (high irradiance) encircled by cold spots (low irradiance) and the irradiance peaks were related to the LED chip locations or the reflections from the reflectors within the body of the LCU.[33,34]

As stated previously, the beam profile of both monowave and polywave LCUs is not homogenous. The monowave Elipar had a much more homogenous output with beam homogeneity factors of 49% compared to the Bluephase Style which only had 2%.[35] The monowave had a higher percent transmittance through the RBC because it has a collimated beam, which may lead to a higher percentage of irradiance going through and not getting lost to the sides of the composite which may happen with the polywave. According to a previous study that compared light-transmission and spectral output of a polywave and monowave LCU through RBCs containing different photoinitiators, monowave activates the CQ more efficiently because its output matches the CQ peak absorption and has higher power in the 420-540nm range.[36]

It is explained previously that when RBCs are photopolymerized using inhomogeneous light sources caused by the power concentration at the locations correlated with the LED chips will result in lower light dispersion through the composite, a highly inhomogeneous photopolymerization across the surface as well as creating differential heating effects within the RBC.[37] This difference may affect the development of polymerization stress, reduce the integrity of the RBC-tooth interfacial bond, and reduce the local physical properties, which may increase the risk of secondary caries underneath the material, hypersensitivity, discoloration or even fracture of the restoration.[28] This problem can be overcome to some extent, but not completely, by preparing thinner composite increments and extending the exposure time beyond the manufacturer's recommended time using high power LCUs, in which the higher overall radiant exposure compensates for the nonuniform LCU beams.[38] Further studies are in progress to determine the effect of beam inhomogeneity as the exposure time of the RBC increases.

For clinical practice, the majority of restoration cavities are smaller than the sample in this study, the larger tip area and more uniform light distribution will cover more of the resin restoration with useful and more uniform irradiance. The position of the RBC under the light tip may also affect the results of microhardness tests. Depending on the light curing orientation, different parts of the RBC restoration will receive different irradiances and different amounts of radiant energy during the same exposure time. Therefore, to ensure that RBCs are adequately photopolymerized, it is important to improve the design of light curing units to deliver a more homogeneous light beam.

Although the present study tested one kind of RBC and light curing unit with 6 shades, there are more resins, light curing units, and shades available on the market. The research design used Teflon molds. Further studies will include more resins, light curing units, and shades and may choose natural tooth mold with a clinically relevant design.

V. Conclusions

Light transmission of RBC decreased with the increasing specimen thickness and with the intensity and opacity of the shades increased.

LCU using inhomogeneous light output can have different effects on the RBC depending on the thicknesses and shades. In the 1-mm thickness case, the microhardness of the RBC performed homogeneous distribution, while in thickness of 2mm or more, the RBC showed inhomogeneous microhardness.

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국문 요약

광조사기 빛의 비균질성이 다른 두께와 색을 갖는 복합레진의 미세강도에 미치는 영향

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목적. 본 연구의 목적은 monowave light-curing unit (LCU)을 이용한 중합시 불균질성이 두께와 색조에 따른 resin-based composite (RBC) 복원의 미세경도에 어떠한 영향을 미치는지 평가하는 것이었다.

방법. 나노필 복합레진 (Filtek Z350)의 body 쉐이드 4 개 (A1B, A2B, A3B, A4B), dentin 쉐이드 1 개 (A3D), enamel 쉐이드 1 개 (A3E)를 선정하였다. 테플론 디스크는 1, 2, 3, 4 mm 의 4 가지 두께로 칼날을 이용하여 절단하였으며, 중앙에 직경 10mm 의 구멍을 뚫었다. 구멍은 Filtek Z350 으로 채우고 40 초 동안 Elipar DeepCure-S 로 중합시킨되었습니다. 분광기 (USB 4000)를 이용하여 분광분포를 구하였다. 37° C 에서 7 일 저장 후 미세경도 값을 측정하였다. Irradiance 는 일원분산분석 (ANOVA) 후 Tukey honest significant difference (HSD) 검정을

이용하여 통계적으로 분석하였다. 두께와 색조가 복합레진의 미세경도에 미치는 영향을 분석하기 위해 Tukey HSD 검정을 이용한 1-way ANOVA 를 사용하였다 ($P=.05$). 측정점이 복합레진의 미세경도에 미치는 효과를 분석하기 위해 LSD (Least Significant Difference) 검정을 통한 repeated 1-way ANOVA 를 사용하였다 ($P=.05$). 각 측정위치에서 RBC 의 irradiance 와 미세경도를 상관시키기 위해 Pearson's correlation 를 이용하였다 ($P=.05$).

결과. Irradiance 은 시편두께가 증가할수록 그리고 색조의 불투명도와 강도가 증가할수록 유의하게 감소하였다 ($P<.05$). 미세경도는 시편 두께가 증가할수록 감소하였다 ($P<.05$). 미세경도는 중심에서 주변부로 갈수록 감소하는 경향을 보였으며, 이러한 경향은 두꺼운 (3, 4-mm) 시편과 어두운 (A3B 및 A4B) 및 불투명한 색조 (A3D) RBC 에서 더욱 뚜렷하게 나타났다 ($P<.05$). Pearson 상관관계 검정을 통해 복합레진의 irradiance 와 모든 측정위치에서 미세경도 사이에 양의 지수상관관계가 나타났다.

결론. 복합레진의 광전달은 두께가 증가할수록 그리고 색조의 강도와 불투명도가 증가할수록 감소하였다. 비균질 광 출력을 사용하는 LCU 는 두께와 색조에 따라 복합레진에 다른 영향을 미칠 수 있습니다. 1 mm 두께의 경우에는 복합레진의 미세경도가 균질한 분포를 보였고, 2mm 이상의 두께에서는 RBC 가 비균질한 미세경도를 보였다.

핵심되는 단어:광중합기; 복합레진; 비균질성; irradiance; 미세경도