Pietra Sanitá Michelin

INFLUÊNCIA DOS APARELHOS FOTOPOLIMERIZADORES NA TRANSMISSÃO DA LUZ E NA MICRODUREZA DE RESINAS COMPOSTAS *BULK-FILL* DE POLIMERIZAÇÃO RÁPIDA EM RESTAURAÇÕES CLASSE II

Influence of light-curing units on light transmission and microhardness of fast-curing bulk-fill resin composites in Class II restorations

Dissertação apresentada à Faculdade de Odontologia da Universidade Federal de Uberlândia, para obtenção do Título de Mestre em Odontologia na Área de Clínica Odontológica Integrada.

Uberlândia, 2025

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Prof. Dr. Carlos José Soares
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Uberlândia, 2025

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M623
2025

Michelin, Pietra Sanitá, 1998-
INFLUÊNCIA DOS APARELHOS FOTOPOLIMERIZADORES NA TRANSMISSÃO DA LUZ E NA MICRODUREZA DE RESINAS COMPOSTAS BULK-FILL DE POLIMERIZAÇÃO RÁPIDA EM RESTAURAÇÕES CLASSE II [recurso eletrônico] / Pietra Sanitá Michelin. - 2025.

Orientadora: Gisele Rodrigues da Silva.
Coorientador: Hugo Lemes Carlo.
Dissertação (Mestrado) - Universidade Federal de Uberlândia, Pós-graduação em Odontologia.
Modo de acesso: Internet.
DOI http://doi.org/10.14393/ufu.di.2025.468
Inclui bibliografia.

1. Odontologia. I. Silva, Gisele Rodrigues da,1982-, (Orient.). II. Carlo, Hugo Lemes,1977-, (Coorient.). III. Universidade Federal de Uberlândia. Pós-graduação em Odontologia. IV. Título.

CDU: 616.314

Bibliotecários responsáveis pela estrutura de acordo com o AACR2:
Gizele Cristine Nunes do Couto - CRB6/2091
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ATA DE DEFESA - PÓS-GRADUAÇÃO

<table>
<tr><td>Programa de Pós-Graduação em:</td><td colspan="5">Odontologia</td></tr>
<tr><td>Defesa de:</td><td colspan="5">Dissertação de Mestrado Acadêmico, nº , PPGODONTO</td></tr>
<tr><td>Data:</td><td>Vinte e oito de julho de dois mil e vinte e cinco</td><td>Hora de início:</td><td>09:30</td><td>Hora de encerramento:</td><td>[11:58]</td></tr>
<tr><td>Matrícula do Discente:</td><td colspan="5">12322ODO025</td></tr>
<tr><td>Nome do Discente:</td><td colspan="5">Pietra Sanitá Michelin</td></tr>
<tr><td>Título do Trabalho:</td><td colspan="5">INFLUÊNCIA DOS APARELHOS FOTOPOLIMERIZADORES NA TRANSMISSÃO DA LUZ E NA MICRODUREZA DE RESINAS COMPOSTAS BULK-FILL DE POLIMERIZAÇÃO RÁPIDA EM RESTAURAÇÕES CLASSE II</td></tr>
<tr><td>Área de concentração:</td><td colspan="5">Clínica Odontológica Integrada</td></tr>
<tr><td>Linha de pesquisa:</td><td colspan="5">Propriedades Físicas e Biológicas dos materiais Odontológicos e das estruturas dentais</td></tr>
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Iniciando os trabalhos o(a) presidente da mesa, Dr(a). Hugo Lemes Carlo, apresentou a Comissão Examinadora e o candidato(a), agradeceu a presença do público, e concedeu ao Discente a palavra para a exposição do seu trabalho. A duração da apresentação do Discente e o tempo de arguição e resposta foram conforme as normas do Programa.

A seguir o senhor(a) presidente concedeu a palavra, pela ordem sucessivamente, aos(às) examinadores(as), que passaram a arguir o(a) candidato(a). Ultimada a arguição, que se desenvolveu dentro dos termos regimentais, a Banca, em sessão secreta, atribuiu o resultado final, considerando o(a) candidato(a):

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DEDICATÓRIA

Dedico este trabalho ao meu pai, Alexandre, à minha mãe, Luciana, à minha irmã, Yasmin, aos meus avós, Maria Luiza, Frederico, Lindaura e José, e ao meu namorado, Guilherme, como sinônimo de muita gratidão por me apoairem em todas as fases da minha vida.

AGRADECIMENTOS

A Deus, por nunca me abandonar, por ter me acompanhado de perto durante esses dois anos e pelo amor incondicional que senti vindo d'Ele todos os dias.

Aos meus pais, Alexandre e Luciana, por me apoiarem em todas as minhas decisões. Obrigada por serem, acima de qualquer coisa, meus melhores amigos. Agradeço pelas orações, por vibrarem a cada conquista minha e por se doarem inteiramente por mim e pela minha irmã, só para nos verem felizes.

À minha irmã, Yasmin, que mesmo longe nunca deixou de ser presente de alguma forma. Obrigada por sempre querer me ver feliz e realizada. Eu tenho um orgulho imenso de você e agradeço a Deus por ter colocado a melhor irmã do mundo para ser minha.

À minha avó, Lindaura, por toda doçura e preocupação comigo sempre. Você é a melhor referência que eu poderia ter. E aos meus avós, Maria Luiza, Frederico e José, que não estão mais aqui, mas ficariam muito orgulhosos dessa minha conquista.

Ao meu namorado, Guilherme, por ser meu parceiro da profissão e da vida, por me apoiar em qualquer decisão e por ser meu amparo em momentos difíceis. Te admiro como profissional e, principalmente, como pessoa. Sou e sempre serei sua fã número um.

A todos os amigos que fiz na pós graduação e que deixaram o caminho mais leve. Às minha amigas da graduação e às amigas de São José do Rio Preto, que continuaram comigo e sempre se fizeram presentes.

À minha orientadora, Gisele, que sempre foi muito solícita e disposta a me ajudar. Tenho uma grande admiração pela profissional que é.

Ao meu co-orientador, Hugo, por ter confiado em mim, por todo amparo e por toda calmaria que sempre me passou. Foi uma supresa muito boa e um presente ter sido orientada por alguém que admiro e que será sempre uma referência para mim. Obrigada, professor, por tornar essa jornada mais tranquila em meio a toda minha ansiedade.

Ao professor Carlos, por toda ajuda e apoio no desenvolvimento deste trabalho e de tantos outros que nos servem de referência.

À Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) e ao Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) pelo apoio financeiro durante esse período.

Ao CPBio (Centro de Pesquisa de Biomecânica, Biomateriais e Biologia Celular), lugar onde tanto aprendi e onde tive muitas oportunidades para executar minha pesquisa da melhor forma.

A todos os funcionarios da FOUFU, por todo amparo e por sempre estarem dispostos a ajudar quando preciso.

EPÍGRAFE

“É justo que muito custe o que muito vale”

Santa Teresa D'Ávila

SUMÁRIO

RESUMO

Objetivo: Avaliar o efeito de diferentes fotopolimerizadores em restaurações classe II de resinas compostas do tipo *bulk-fill* de polimerização rápida e convencional. **Materiais e Métodos:** Dois fotopolimerizadores do tipo LED *multiwave* (Bluephase PowerCure – Ivoclar Vivadent, Schaan, Liechtenstein; Quazar – FGM, Joinville, SC, Brasil) foram utilizados para polimerizar os materiais testados nos modos 3s – alta irradiância e curto tempo de exposição; e 20s – irradiância padrão e tempo padrão. Os aparelhos foram caracterizados quanto à potência radiante (mW), diâmetro interno da ponteira (mm), irradiância da ponteira (mW/cm²), espectro de emissão (mW/cm²/nm) e perfil de irradiância (mW/cm²). O espectro de emissão foi avaliado através dos materiais a 1, 3 e 4mm de profundidade com o uso de um espectrômetro acoplado a uma esfera integradora. Os perfis de irradiância foram obtidos com um analisador de feixe e avaliados nas mesmas profundidades. Restaurações classe II do tipo MOD (3×6×4mm) foram realizadas em pré-molares artificiais (Oclusal – Oclusal Produtos Odontológicos Ltda, São Paulo, SP, Brasil) utilizando-se quatro resinas do tipo *bulk-fill*, sendo duas do tipo fluida (Tetric N-Flow Bulk Fill – Ivoclar Vivadent, Schaan, Liechtenstein; Tetric PowerFlow – Ivoclar Vivadent, Schaan, Liechtenstein) e duas de alta viscosidade (Tetric N-Ceram Bulk Fill – Ivoclar Vivadent, Schaan, Liechtenstein; Tetric PowerFill – Ivoclar Vivadent, Schaan, Liechtenstein). Foram utilizadas duas técnicas restauradoras (*bulk-fill* fluida + *bulk-fill* de alta viscosidade ou *bulk-fill* de alta viscosidade). As resinas de polimerização rápida (Tetric PowerFill e Tetric PowerFlow) foram fotopolimerizadas no modo de 3s, enquanto as resinas de polimerização convencional (Tetric N-Flow e Tetric N-Ceram) foram polimerizadas no modo 20s. A profundidade regional de polimerização foi determinada por meio de microdureza Knoop nas profundidades de 0,5; 1; 2; 3 e 4mm, nas regiões mesial, central e distal. Os resultados de potência radiante, diâmetro interno da ponteira, irradiância da ponteira, espectro de emissão e perfis de irradiância foram analisados de modo descritivo. Os dados de profundidade regional foram testados quanto à normalidade (Shapiro-Wilk) e homogeneidade de variância (Levene). Em seguida utilizou-se o teste ANOVA de medidas repetidas seguido do teste post-hoc de Tukey (α=5%). **Resultados:** Os valores de irradiância apresentarm-se semelhantes entre os aparelhos. Os maiores resultados foram observados no modo 3s. A exposição radiante aumentou com o tempo de exposição. A transmissão de luz diminuiu com o aumento da espessura da camada de resina. Considerando a profundidade regional de polimerização, observaram-se diferenças estatísticas significantes para os fatores profundidade ($p<0,001$) e tipo de resina ($p<0,001$), mas não para região ($p=0,283$) e para aparelho de fotopolimerização ($p=0,174$). A microdureza diminuiu com o aumento da profundidade. Resinas de baixa viscosidade apresentaram menores valores de microdureza em comparação com as de alta viscosidade. **Conclusão:** A transmissão de luz e a profundidade de polimerização diminuíram conforme se aumentou a espessura das resinas; alta irradiância em curto tempo de exposição resultaram em valores de microdureza regionais semelhantes aos obtidos com irradiância padrão e tempo de exposição padrão, independente do aparelho fotopolimerizador.

Palavras-chave: Resinas Compostas; Polimerização de Resinas Dentárias; Unidades de Fotopolimerização; Dureza Knoop.

ABSTRACT

Aim: To evaluate the effect of different light-curing units on Class II restorations of bulk-fill resin composites using fast and conventional polymerization protocols. **Materials and Methods**: Two multiwave LED light-curing units (Bluephase PowerCure – Ivoclar Vivadent, Schaan, Liechtenstein; Quazar – FGM, Joinville, SC, Brazil) were used to polymerize the tested materials under two modes: 3s (high irradiance, short exposure time) and 20s (standard irradiance and standard exposure time). The devices were characterized based on radiant power (mW), tip internal diameter (mm), tip irradiance (mW/cm²), emission spectrum (mW/cm²/nm), and irradiance profile (mW/cm²). The emission spectrum was evaluated through the materials at depths of 1, 3, and 4mm using a spectrometer coupled to an integrating sphere. Irradiance profiles were obtained using a beam profiler and analyzed at the same depths. Class II MOD restorations (3×6×4mm) were performed in typodont premolars (Oclusal – Oclusal Produtos Odontológicos Ltda, São Paulo, SP, Brazil) using four bulk-fill composites: two low-viscosity (Tetric N-Flow Bulk Fill and Tetric PowerFlow – Ivoclar Vivadent, Schaan, Liechtenstein) and two high-viscosity (Tetric N-Ceram Bulk Fill and Tetric PowerFill – Ivoclar Vivadent, Schaan, Liechtenstein) materials. Two restorative techniques were used: low-viscosity bulk-fill + high-viscosity bulk-fill, or high-viscosity bulk-fill. The fast-curing resins (Tetric PowerFill and Tetric PowerFlow) were polymerized using the 3s mode, whereas the conventional resins (Tetric N-Flow and Tetric N-Ceram) were cured using the 20s mode. Regional polymerization depth was assessed using Knoop microhardness at 0.5, 1, 2, 3, and 4mm depths in the mesial, central, and distal regions. Radiant power, tip diameter, tip irradiance, emission spectrum, and irradiance profiles were descriptively analyzed. Regional depth data were tested for normality (Shapiro-Wilk) and homogeneity of variance (Levene). Repeated-measures ANOVA followed by Tukey's post-hoc test was used (α=5%). **Results:** Irradiance values were similar between devices. Higher results were observed in the 3s mode. Radiant exposure increased with longer exposure time. Light transmission decreased with increasing resin thickness. Regarding regional polymerization depth, statistically significant differences were found for depth ($p<0.001$) and resin type ($p<0.001$), but not for region ($p=0.283$) or light-curing unit ($p=0.174$). Microhardness decreased as depth increased. Low-viscosity resins showed lower microhardness values. **Conclusion:** Light transmission and polymerization depth decreased as resin thickness increased. High irradiance with short exposure time produced regional microhardness values comparable to those achieved with standard irradiance and standard exposure time, regardless of the light-curing unit used.

Keywords: Composite Resins; Dental Resin Polymerization; Light-Curing Units; Knoop Hardness.

1. INTRODUÇÃO E REFERENCIAL TEÓRICO

As resinas compostas são os materiais mais comumente utilizados para restauração de dentes cariados, fraturados ou restaurações estéticas (Heintze *et al.,* 2022). A composição do material consiste em misturas de diferentes monômeros à base de metacrilato, cujo componente principal é o Bisfenol-A glicidilmetacrilato (Bis-GMA), e cargas inorgânicas revestidas de silano (Fronza et al., 2019). Além disso, apresentam fotoiniciadores que iniciam o processo de polimerização quando submetidas à luz em um comprimento de onda específico, formando uma rede reticulada com excelentes propriedades mecânicas (Stansbury, 2012). A composição destes materiais apresenta uma constante evolução desde que foram introduzidos no mercado (Ferracane, 2011). Há cerca de uma década, foram introduzidas no mercado, as resinas compostas do tipo *bulk-fill*, que podem ser inseridas em incrementos únicos no interior de cavidades, podendo ser polimerizadas em profundidades de até 4-5mm (Rosatto et al., 2015). Tais materiais possuem alterações em sua composição que permitem uma melhor dissipação da luz através da resina que permitiram diminuir o tempo de trabalho, devido à menor quantidade de incrementos, gerando menos tensões de contração (Van Ende et al., 2017).

As resinas compostas possuem diferentes viscosidades. Materiais de baixa viscosidade (fluidas ou *flow*) apresentam um maior escoamento, conseguindo se adaptar melhor ao interior de uma cavidade (Peutzfeldt et al., 2018). No entanto, devido a um menor conteúdo de cargas inorgânicas, apresentam propriedades mecânicas reduzidas (Comba et al.,2020). Desta forma, quando utilizadas, devem ser cobertas um incremento de resina de alta viscosidade (Jang et al., 2015). Os materiais de alta viscosidade possuem maior quantidade de partículas de carga. Sua utilização como material de cobertura melhora as propriedades mecânicas da restauração e evita maior absorção de água pelo material fluido (Jung & Park, 2017).

Recentemente foram introduzidas no mercado resinas de polimerização rápida, que são materiais que podem ser polimerizados pelo tempo de 3s utilizando-se aparelhos fotopolimerizadores de alta irradiância. Esta polimerização rápida é possível devido a mudanças na matriz orgânica do material e adição de fotoiniciadores alternativos (Todd, 2024), visando reduzir a contração de polimerização e a tensão de contração (Algamaiah et al., 2021). Esses materiais também estão disponíveis em duas viscosidades (alta e baixa). Dentre as mudanças na composição do material, pode-se citar a adição de um reagente, β-alil sulfona, capaz de promover uma reação de transferência de cadeia de fragmentação por adição (AFCT), que modifica a reação de polimerização para que possam ser geradas cadeias poliméricas mais curtas, que crescem de forma mais controlada e uma estrutura mais homogênea (Gorsche et al., 2015).

O processo de fotopolimerização é uma etapa imprescindível para garantir propriedades mecânicas adequadas para os compósitos resinosos (Lise et al., 2018). Uma quantidade adequada de luz em um comprimento de onda específico é necessária para conseguir sensibilizar os fotoiniciadores dos materiais (Palin et al., 2018). O fotoiniciador mais comumente utilizado é a canforoquinona, um iniciador do tipo Norrish Tipo II que responde melhor à luz em torno de 470nm (Alvim et al., 2007). Nas resinas de polimerização rápida, fotoiniciadores alternativos foram adicionados. Além da canforoquinona, esses compósitos apresentam Ivocerin, patenteado pelo mesmo fabricante dessas resinas de polimerização rápida, e Lucirin TPO em sua composição (Todd, 2024). Esses, pertencem aos fotoiniciadores Norrish Tipo I, e têm os máximos de absorção na parte violeta do espectro, ou seja, são mais sensíveis à luz em comprimentos de onda mais curtos (<420nm) (Ilie & Hickel, 2008). São altamente reativos e, por esse motivo, são usados em materiais que visam aumentar a profundidade de polimerização (Harlow et al., 2016).

Para que seja possível polimerizar adequadamente as resinas de polimerização rápida, é preciso que a unidade fotopolimerizadora seja compatível com o modo de polimerização delas. As resinas de polimerização rápida possuem indicação de serem polimerizadas em um tempo de 3s com uma alta irradiância (2700–3300mW/cm²) no espectro azul-violeta (Todd, 2024). Sendo assim, é necessário a utilização de uma fonte multi-wave, ou seja, com múltiplos picos de emissão (Braga et al., 2022). Desta forma, é possível sensibilizar da melhor forma os fotoiniciadores alternativos, que são melhor sensibilizados em comprimentos de onda menores, com luz violeta (Neumann et al., 2006).

A redução do tempo de fotoativação requer atenção, pois pode levar à baixa conversão de monômeros e, consequentemente, alterar as propriedades mecânicas dos materiais restauradores (Sampaio et al., 2017). Desta maneira, torna-se importante avaliar o efeito que diferentes unidades fotopolimerizadoras podem exercer sobre a polimerização de resinas compostas de polimerização rápida, comparando-as com resinas de polimerização convencional. Além disso, há a necessidade de se verificar como esse processo ocorre em diferentes regiões e profundidades de um preparo cavitário. Assim, o presente estudo analisou o efeito de duas unidades fotopolimerizadoras na microdureza, em profundidade, de resinas compostas de polimerização rápida e polimerização convencional, em diferentes regiões de preparos cavitários classe II em dentes pré-molares artificiais. Também foi realizada a caracterização das unidades fotopolimerizadoras, verificado-se os espectros de emissão e os perfis de irradiância através dos diferentes materiais.

2. OBJETIVO

Avaliar o efeito de duas unidades fotopolimerizadoras na polimerização de resinas compostas do tipo *bulk-fill* de polimerização rápida e polimerização convencional, determinando-se a microdureza em profundidade nas regiões mesial, central e distal de restaurações realizadas em preparos cavitários classe II do tipo MOD em pré-molares artificiais. As unidades fotopolimerizadoras foram caracterizadas quanto à potência radiante, diâmetro interno da ponteira, irradiância da ponteira, espectros de emissão e perfis de irradiância. Verificou-se, também, os espectros de emissão e os perfis de irradiância através dos diferentes materiais

3. CAPÍTULO 1

Artigo a ser submetido ao periódico Journal of Dentistry

Influence of light-curing units on light transmission and regional microhardness of fast-curing bulk-fill resin composites in Class II restorations

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Acknowledgments

This study was supported by grants from the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior- Brazil (CAPES #001) and Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) - INCT Saúde Oral e Odontologia - Grants n. 406840/2022-9.

Conflict of interest statement

The authors report no conflicts of interest related to this study

ABSTRACT

OBJECTIVE. To evaluate the effect of different light-curing units (LCUs) on fast and convencional curing bulk-fill resin composite restorations. **METHODS.** Four bulk-fill resins (Tetric N-Flow, Tetric N-Ceram, Tetric PowerFlow, and Tetric PowerFill – Ivoclar Vivadent, Schaan, Liechtenstein) were used to restore standardized MOD cavities (3×6×4mm) on typodont premolars, following two restorative techniques. Fast-curing resins were light-cured for 3s while conventional-curing resins were light-cured for 20s, using Bluephase Powercure (Ivoclar Vivadent, Schaan, Liechtenstein) and Quazar (FGM, Joinville, SC, Brazil). The LCUs were characterized by radiant power, tip diameter, irradiance, emission spectra, and irradiance profiles. Light transmission was analyzed at 1, 3, and 4mm depths using a spectrometer connected to an integrating sphere. Irradiance profiles were measured at the same depths using a beam profiler. Depth of cure was determined through Knoop microhardness at 0.5, 1, 2, 3, and 4 mm on mesial, central, and distal regions. Data were analyzed using repeated measures ANOVA followed by Tukey's post-hoc test ($\alpha=0.05$).

RESULTS. Irradiance values were similar between LCUs, with higher radiant exposure at 20s. Light attenuation increased with material thickness. Microhardness significantly differed by depth ($p<0.001$) and resin type ($p<0.001$), but not for regions ($p=0.283$) and LCU ($p=0.174$). The microhardness decreased with thickness with high-viscosity resins showing higher values.

CONCLUSION. Light transmission and depth of cure decreased with thickness. The 3s irradiance produced similar results as 20s, regardless of the LCU tested.

CLINICAL SIGNIFICANCE. Fast-curing bulk-fill resins showed similar results to conventional materials regardless of the LCU.

Keywords: Composite Resins; Dental Resin Polymerization; Light-Curing Units; Knoop Hardness.

INTRODUCTION

Bulk-fill composites allow a single-step increment cavity filling to achive great polymerization up to 4-5mm depth and reduced shrinkage stress [1,2]. These materials present greater translucency due to changes in the amount and quality of filler particles, resulting in greater light transmission through the material. More reactive photoinitiators were added, enabling increased depth of polymerization and new monomers were included to act as modulators of the polymerization reaction, contributing to reduced shrinkage [3,4,5,6,7]. They are commercially presented in two viscosities: low viscosity (flow) and high-viscosity. The flowable materials are easy handling, with better fluidity, and improved internal marginal adaptation. However, due to a lower content of inorganic fillers, they may exhibit reduced mechanical properties [8] and the covering with a high-viscosity resin is recommended [9].

A manufacturer developed bulk-fill resins modified for shorter intervals of photocuring recently [10]. The fast-curing bulk-fill resins are indicated to be cured for 3s with high radiant curing lights (2700–3300 mW/cm²) in the blue-violet light spectra [10,11,12]. To achieve this reduced curing time, modifications on the organic matrix of the material were necessary to avoid adverse consequences. A reagent (β-allyl sulfone) was incorporated into the organic matrix promoting chain fragmentation addition transfer (AFCT), altering the polymerization reaction and producing shorter polymer chains, a more homogeneous structure, and a lower glass transition temperature [13,14]. This happens because the reagent interrupts the formation of long polymer chains while simultaneously generating free radicals that initiate new propagation chains. A mixed polymerization reaction occurs, with simultaneous chain and radical growth, producing improved mechanical properties [14,15]. A light curing unity (LCU) with high irradiance were developed by the same manufacturer of the fast-curing resins and it was indicated to photocure them [16]. It is a multi-wave LED emiting light with both violet (380–420 nm) and blue (420–490 nm) spectra [17].

Although the recommended restorative technique for bulk-fill composites allows increments up to 4–5mm, certain considerations must be taken into account [18]. It is important to emphasize that the botton of the restoration may not receive the same amount of energy as the top due to light attenuation despite the high translucency of the material [19,20]. Therefore, properties such as microhardness may not be acceptable in the lower layers [21,22]. Additionally, the literature has shown conflicting results regarding the reduction in exposure time and decrease of irradiance related to depth of cure [23,24].

The objective of this study was to evaluate the effect of two different LCUs on fast-curing bulk-fill resins and conventional bulk-fill resins restorations analyzing the regional microhardness depth of cure on class II MOD restorations (3x6x4mm) on typodont premolars. The LCUs were characterized to radiant power (mW), irradiance (mW/cm²), emission spectra (mW/cm²/nm), and irradiance profiles (mW/cm²). Transmission spectra was determined through the materials and was assessed at different depths. The null hypotheses tested were: (1) There would be no differences in the microhardness regional depth between fast-curing and conventional bulk-fill resins; (2) The two LCUs tested should not interfere in the microhardness regional depth; and (3) Light transmission would not be affected by the material thickness.

MATHERIALS AND METHODS

Four bulk-fill resin composites were tested. A low-viscosity bulk-fill resin (Tetric N-Flow Bulk Fill – Ivoclar Vivadent, Schaan, Liechtenstein), a high-viscosity bulk-fill resin (Tetric N-Ceram Bulk Fill – Ivoclar Vivadent, Schaan, Liechtenstein), a fast-cure low-viscosity bulk-fill resin (Tetric PowerFlow – Ivoclar Vivadent, Schaan, Liechtenstein), and a fast-cure high-viscosity bulk-fill (Tetric PowerFill – Ivoclar Vivadent, Schaan, Liechtenstein) (Table 1). The resin composites were light cured using two LCUs (Bluephase Powercure – Ivoclar Vivadent, Schaan, Liechtenstein, and Quazar – FGM, Joinville, SC, Brazil) (Table1) using high irradiance (≈3,000 mW/cm²) and short exposure time (3s) for the fast-cure bulk-fill resins or standard irradiance (≈1,000 mW/cm²) and standard exposure time (20s) for the others.

Sample Calculation

The sample size calculation for the microhardness test was performed using a free online sample size calculator (http://calculoamostral.bauru.usp.br/calculoamostral - FOB/USP).

For the analysis of the continuous quantitative variable "microhardness," the results from the study by Rosatto et al. (2015) were considered. The samples were treated as independent. The statistical power of the test was set at 80%, with a two-tailed alpha of 5% and a minimum detectable difference of 10, resulting in a requirement of ten samples per group (n=10).

LCUs Output and Spectra Transmission

The LCUs were characterized for radiant power (mW), external tip diameter (mm), internal tip diameter (mm), energy output (J/cm²), and emission spectra (mW/cm²/nm). A six-inch integrating sphere (Labsphere – North Sutton, NH, USA) connected to a fiber optic spectrometer (Flame-T – Ocean Insight, Orlando, FL, USA) was used to measure total radiant power and tip irradiance in both standard (20s) and high-power (3s) modes. The system was previously calibrated using an internal calibration lamp (SCL-600 – Labsphere – North Sutton, NH, USA).

Characterization was performed at a total sphere aperture of 12.5mm. A digital caliper (Mitutoyo, Tokyo, Japan) was used to determine the internal and external diameters of the LCU tips. The mean irradiance at the light tip surface (mW/cm²) was calculated by dividing the radiant power (mW) by the optical area of the internal tip (mm²). All spectral data (mW/nm) were collected and analyzed using OceanView software (Ocean Insight – Orlando, FL, USA). Radiant exposure (J/cm²) was calculated by multiplying the irradiance (mW/cm²) by the exposure time (s).

In addition, spectral transmission through resin composites was assessed and evaluated for both LCUs. Transmission was analyzed using custom matrices fabricated with a FDM-type 3D printer (Bambu Lab X1 Carbon – Bambu Lab, Shenzhen, GD, China) and PLA Filament (Bambu Lab, Shenzhen, GD, China). Each matrix had a total diameter of 15mm and a central rectangular aperture (6x3mm) with different depths (1.0, 3.0, and 4.0mm), as shown in Figure 1. The matrices were printed with these dimensions to simulate the MOD cavities of the typodont teeth and the resin composite increment. This approach allowed for limiting the sphere's aperture size to a more compatible with the MOD cavity used. Three matrices were printed for each thickness to allow for averaging these three values (n=3). The resin-filled matrices were positioned at the integrating sphere's entrance for spectral transmission measurements. Reference measurements (baseline) were performed with empty 0.5mm-thick matrices (without resin). The LCU tip was positioned in direct contact with the 1.0mm and 4.0mm-thick matrices. For the 3.0mm-thick, the LCU tip was positioned 1mm away from the matrix to simulate the curing protocol for low-viscosity bulk-fill resins. Spectral transmission analyses were conducted at these three thicknesses due to the two restorative techniques tested (high-consistency bulk-fill resin or low-viscosity bulk-fill resin + high-consistency bulk-fill resin). All samples were light-cured with both LCUs for 3s in high irradiance mode (≈3,000 mW/cm²) for the fast-curing composites and for 20s in standard irradiance mode (≈1,000 mW/cm²) for the conventional composites.

The irradiance profiles transmitted through different resin thicknesses were measured using a CCD (charge-coupled device) digital camera designed for laser beam profile analysis (Ophir-Spiricon, Logan, UT, USA), equipped with a 50mm focal length lens (SP620U; Ophir-Spiricon). The LCUs were positioned at a fixed distance of 0mm from the imaging screen or the resin-filled matrices, facing the camera. For the control condition, a 40-degree holographic diffuser screen (Edmund Optics, Barrington, NJ, USA) was placed at the same focal distance as the digital camera. No diffuser screen was necessary during light transmission through the resin samples, as these acted as the diffusing medium. Two blue bandpass filters (HOYA UV-VIS – Edmund Optics, Barrington, NJ, USA) and three reflective neutral density filters (OD 1.0, 2.0, and 3.0 – Edmund Optics) were used to attenuate light intensity and correct the CCD sensor's spectral response. Images of the irradiance profiles were captured with the beam analysis software (BeamGage Professional, version 6.14 – Ophir-Spiricon, Logan, UT, USA). For the control irradiance profile (light transmitted without resin), the internal tip diameter of each LCU (mm) was used, and the "Optical Scaling" tool in BeamGage Professional was applied to calibrate the beam profile data (mm). The previously measured average radiant power values (mW) were entered into the beam analysis software to generate calibrated and color-coded irradiance maps (mW/cm²), where red indicates areas of high irradiance (100% or maximum) and purple indicates areas of low irradiance at the light tip's extremity. The calibrated beam data from BeamGage Professional were then exported to OriginPro 2025 (OriginLab, Northampton, MA, USA), where all images were adjusted to the same irradiance levels and scaled with consistent dimensions on the x and y axes.

Regional Depth of Cure (Microhardness)

The determination of regional depth of cure was performed through microhardness analysis. Eighty typodont premolars (Oclusal – Oclusal Produtos Odontológicos Ltda, São Paulo, SP, Brazil), with standardized Class II MOD cavities (4mm depth x 3mm width x 6mm length) were used (n=10).

For the restorative procedure, the internal surfaces of the cavity preparations were sandblasted with aluminum oxide to enhance adhesion on the non-reactive substrate. Subsequently, a universal adhesive system (Tetric N-Bond Universal – Ivoclar Vivadent AG, Schaan, Liechtenstein) was applied in a single step, spreaded for 20s and air-dried for 10s. The adhesive was then light-cured for 5s with each LCUs (High Power mode for 5s using Quazar and T-mode for 5s using Bluephase PowerCure). To reconstruct proximal wall contours, anatomical wooden wedges (TDV Dental Ltda, Pomerode, SC, Brazil) and Tofflemire matrix system (Golgran, São Caetano do Sul, SP, Brazil) were used. All procedures were carried out in an upper typodont dental arch (Oclusal – Oclusal Produtos Odontológicos Ltda, São Paulo, SP, Brasil), enabling interproximal contact during restoration.

Two restorative techniques were carried out using the four resins: 1. Low-viscosity bulk-fill resin + high-viscosity bulk-fill resin – the low-viscosity bulk-fill resin was isserted in a 3mm increment and light-cured followed by a 1mm layer of a high-viscosity bulk-fill resin; 2. High-viscosity bulk-fill resin – the high-viscosity bulk-fill resin was inserted in a 4mm single increment. Each increment was photocured for 3s in high irradiance mode for the fast-curing composites and for 20s in standard irradiance mode for the conventional composites. The LCU tip was positioned in the center of the cavity, and a single polymerization was performed for each resin increment.

Each tooth was sectioned mesiodistally using a silicon carbide abrasive disc (American Burrs – American Dental Systems, São Paulo, SP, Brazil) attached to a low-speed handpiece motor (NSK – Nakanishi Inc., Kanuma, Tochigi, Japan), resulting in two halves. The vestibular half was embedded in epoxy resin (Polipox, São Paulo, SP, Brazil). The sample surfaces were polished using silicon carbide papers (#600, 1200, and 2000 grit – 3M, Campinas, SP, Brazil) and diamond polishing pastes (6, 3, 1, and 0.25 µm – Arotec, São Paulo, SP, Brazil). Cleaning was performed in an ultrasonic bath with distilled water for 3min. Microhardness was obtained with a Knoop indenter (FM-7000, Future-Tech Corp, Kawasaki, Kanagawa, Japan) with a controlled force of 50g for 15s. Measurements were performed at five depths (0.5, 1.0, 2.0, 3.0, and 4.0mm from the occlusal surface of the restoration) at three regions (mesial, central and distal). Three indentations were made per region at each depth and the mean values were used.

Statistical analysis

Statistical analysis was conducted using Jamovi software (version 2.6; The jamovi project, 2024). The analysis wwere descriptive for radiant power, internal tip diameter, tip irradiance, emission spectra and irradiance profiles. Regional depth of cure data was collected and analyzed for normality (Shapiro-Wilk test) and homogeneity of variance (Levene's test). Repeated measures ANOVA test was conducted followed by Tukey's post-hoc test. A significance level of 5% was adopted for all tests.

RESULTS

The mean and standard deviation of output power (mW), irradiance (mW/cm²), and radiant exposure (J/cm²) provided by the two LCUs are presented in Table 2. It was observed that the Quazar light-curing unit exhibited the highest output power values. In contrast, irradiance values were similar between units, with the highest results corresponding to the 3s mode for both LCUs. Regarding radiant exposure, the values increased proportionally with longer exposure times. Therefore, the highest radiant exposure values for both LCUs were observed for the 20s mode. Furthermore, a noticeable decrease in all values was observed when the matrix, which delimits the opening of the integrating sphere, was interposed. Nevertheless, the highest radiant exposure values remained associated with the 20s mode.

The irradiance profiles of the two LCUs in both modes (3s and 20s) are presented in Figure 2. The smaller diameter of the Bluephase Powercure tip compared to the Quazar is noticeable. Once again, it is evident that the highest irradiance values were observed in the shorter exposure times (3s) for both devices.

Spectra transmission through the resin samples is shown in Figure 3. The irradiance profiles indicated that spectra transmission was affected by sample thickness. It decreased for both LCUs as the resin thickness increased, regardless of the resin or curing mode (3s or 20s).

Figure 4 shows that the 3s mode provided the highest spectral radiant power and irradiance for both LCUs. Quazar LCU presented the highest power values (Table 2). Figures 5 and 6 shows the power and absolute spectral irradiance transmitted through the resin composite using both LCUs in the 20s and 3s mode. Both power and spectral irradiance decreased as resin thickness increased, regardless of the LCU or resin. In the 3s mode, Bluephase Powercure LCU showed higher absolute spectral irradiance values for 1mm-thick and similar values for to 3mm and 4mm-thick when compared to Quazar LCU.

Microhardness regional depth (Table 3) showed normal distribution (Shapiro-Wilk test – $p>0.05$) and homogeneity of variance (Levene's test – $p>0.05$), and the repeated-measures ANOVA test revealed statistical significance for the factors depth ($p<0.001$) and resin ($p<0.001$), but not for region ($p=0.283$) and LCU ($p=0.174$). Statistical significance was observed for the interaction between depth and resin ($p<0.001$), but not for depth × resin × region ($p=0.065$), depth × region × LCU ($p=0.373$), and depth × resin × region × LCU ($p=0.774$). Tukey's post-hoc test was used. The results indicated a decrease in microhardness values as depth increased and flow-viscosity resins showed lower values when compared to high-viscosity. No significant differences were found between the LCUs or among the regions at the same depth.

Figure 7 presents the hardness profiles for the central region groups across all resins and for both LCUs. The hardness profiles show a consistent decrease in polymerization depth for all composites and LCUs combinations.

DISCUSSION

Four resin composites and two light-curing units were tested in this study. The first and second null hypotheses were accepted, since both the fast-curing and conventional bulk-fill resins, as well as the two light-curing units, showed no differences in regional microhardness depth. However, the third null hypothesis was rejected, as light transmission was affected by material thickness.

The high-irradiance mode with a short exposure time (3s) was used only for the fast curing resins. It is supported by previous studies, which have concluded that this cure mode should be restricted to resins specifically formulated for it [23,25,26]. The 3s exposure time resulted in reduced radiant exposure (J/cm^2), consistent with what has already been reported in the literature [21]. While the 20s exposure time delivered $12.6 J/cm^2$ and $15.5 J/cm^2$, respectively, the 3s mode delivered less than half of that energy ($4.5 J/cm^2$ and $6.1 J/cm^2$) [27]. With lower energy delivery, the degree of conversion should be lower, directly impacting in the properties of the resin composites [28]. But fast-curing resins were modified in their formulations. They show changes in the organic matrix and includes a reversible addition–fragmentation chain-transfer (RAFT) polymerization mechanism through the addition of a β-allyl sulfone (AFCT) reagent. The RAFT method allows control over the growth of polymer chains by transferring radicals between them, resulting in stepwise polymerization, more homogeneous chain growth, network formation, and delaied gel point [29]. It was observed that this modification allows for a 3s curing with high irradiance protocol to be comparable to a standard 20s irradiance [24,29,30]. These findings are consistent with the results of the present study, which demonstrated that there was no significant difference between the curing modes.

In addition to the modifications cited, it is important to highlight that the initiator system also underwent changes, which help explain the findings of the present study. The addition of photoinitiators such as Ivocerin™ and Lucirin-TPO, combined with camphorquinone (CQ) – a combination of Norrish type I and II photoinitiators – can lead to faster polymerization kinetics. Along with changes in the organic matrix, it also helps improving the degree of conversion [31]. For adequate resin composite conversion, both irradiance and exposure time must be sufficient, due to the different quantum yields and absorption coefficients of photoinitiators [32,33]. However, this photoinitiator system achieves a higher degree of conversion when higher irradiance is applied during shorter periods. In this context, power density plays a greater role than time, which contrasts with the behavior of CQ-based systems [34]. Alternative photoinitiators do not require co-initiators and absorb violet light (<420nm), i.e., shorter wavelengths [31,35]. For this reason, it is essential to use a light source with a spectral output that matches the absorption spectrum of the photoinitiator to ensure optimal material performance, comparable to conventional curing protocols [35,36]. Therefore, in this study, only dual-peak multiwave light-curing units were used – one peak in the violet range (395–415nm) and the other in the blue range (450–470nm). Both the Bluephase PowerCure LCU, this one belonging to the same manufacturer of the resins tested, and the Quazar LCU provided broad spectral coverage, with wavelength ranges ideal for effective absorption by the photoinitiator system of the resins.

Although the Quazar LCU exhibited slightly higher power output than the Bluephase Powercure LCU, its irradiance and total energy delivery were similar or even lower. This can be explained by the tip diameters. Bluephase presented a diameter of 8.2mm, whereas Quazar presenteded a diameter of 9.9mm. A smaller tip area concentrates light energy, thereby increasing irradiance [35].

Irradiance is defined as radiant power per unit area (W/cm²). This also explains the findings illustrated in Figure 3, where light transmission through different composite thicknesses was greater when using the Bluephase Powercure LCU. A smaller matrix aperture favors a LCU with a smaller tip diameter, concentrating more energy in a confined area. However, in clinical scenarios, narrow apertures may limit light penetration, potentially resulting in insufficient polymerization [37].

The microhardness test results showed no statistically significant differences between the LCUs (p=0.174). As previously mentioned, despite differences in power output, both units delivered similar amounts of energy in both curing modes. As a result, the degree of conversion became similar and reflecting in the same mechanical property. Another relevant finding was the absence of significant differences in hardness among the mesial, central, and distal regions (p=0.283). This can be attributed to the size of the MOD cavity of the upper premolar used. The tip diameters of the LCUs (Bluephase PowerCure – 8,2mm and Quazar – 9,9mm), exceeded the cavity dimensions (3mm in width and 6mm in length), so all regions received similar amounts of energy, even with just a single light exposure in the center of the sample. However, if working in a large cavity (molars i.e.), multiple light exposures should be necessary to fully cover the entire cavity [35].

The images in Figure 3 also suggest a decrease in light reaching the bottom of the composite as material thickness increased. This corresponds to the results of another study, in which light penetration into the composite significantly decreased with increased restoration depth (especially for violet light) [21]. Light reaching the surface of the composite is not distributed homogeneously, and the energy that reaches the bottom of the restoration tends to decrease, potentially affecting the degree of conversion [21,22]. Since the degree of conversion is correlated with hardness, Table 3 shows that microhardness decreased as the restoration depth increased (p<0.001), which is also consistent with several other investigations [19,23,24,38,39,40,41]. Adequate polymerization of resin composites is achieved when the bottom-to-top hardness ratio reaches at least 80% [42]. In this study, this ratio was reached for all groups using a single-increment technique with high-viscosity resins. Regarding the low-viscosity composites, the 80% ratio propably was not reached due to the presence of the high-viscosity resin layer due to its higher inorganic filler content [18,20,21,22,43].

The technique of initially filling the cavity with flowable composites followed by a high-viscosity composite capping layer is widely recommended [9]. This strategy enhances mechanical properties such as surface hardness and prevents higher water sorption by the flowable material [44]. Flowable composites present better adaptability, improving marginal integrity at the base of the dental cavity [8].

Although no statistically significant differences in microhardness were observed between the curing protocols, it is important to recognize limitations in comparing results from studies employing varied methodologies and approaches. Furthermore, when analyzing the fast-curing mode, as previously mentioned, although it delivered higher power and irradiance, it did not result in the highest radiant exposure. Therefore, this mode should be restricted to materials specifically designed for such protocols. Another critical consideration is that a 3s exposure time is extremely short. A minor deviation from optimal curing conditions, such as tip misalignment or increased distance from the material, can significantly impact the polymerization process and, consequently, the final properties of the material. Ilie and Watts emphasized that reducing the 3s curing time by just 1s corresponds to a 33% reduction in radiant exposure [30].

Although shortening clinical time by reducing resin composite curing period seems to be attactive, it requires caution and a thorough understanding of the mechanical behavior of bulk-fill composites under different light-curing protocols. This study demonstrated that no significant differences were observed between curing modes with the different LCUs. However, cavity depth significantly affected polymerization efficiency, which directly influenced the microhardness of the restorative materials. The observation that flowable composites exhibited lower microhardness also reinforces the importance of subsequently inserting a high-viscosity resin increment to ensure the long-term success and performance of restorations in posterior teeth. Therefore, within the limitations and ideal light-curing conditions of this study, it should be important to corroborate this in vitro results with more clinical data.

CONCLUSION

Based on the results and the limitations of the present study, it can be concluded that:

- Light transmission was attenuated as the resin thickness increased;
- The depth of polymerization influenced the hardness of the resin composites, but an adequate curing of the resin composites was achieved as the bottom-to-top hardness ratio reached at least 80%;
- The region (mesial, distal, or central) did not influence the microhardness results of the resin composites tested;
- The LCUs had no significant effect on the microhardness of the resin composites tested;
- Low-viscosity resins exhibited lower hardness values when compared to higher-viscosity resins.

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Tables

Table 1. Composite resins and light curing units (LCU) tested

Resin Composite LCU	Commercial Brand Manufacturer (batch number/serial number)	Composition/Details*
Low-viscosity Bulk-Fill Resin Composite (shade IVA)	Tetric N-Flow Bulk Fill - Ivoclar Vivadent AG, Schaan, Liechtenstein (Z0624V)	Organic phase: Bis-GMA, Bis-EMA, TCDDMA. Inorganic phase (68.2 wt.%): Barium glass, ytterbium trifluoride, and copolymers. Photoinitiators: CQ and Ivocerin, stabilizers and pigments (<1.0 wt.%)
High-viscosity Bulk-Fill Resin Composite (shade IVA)	Tetric N-Ceram Bulk Fill - Ivoclar Vivadent AG, Schaan, Liechtenstein (Z06NBW)	Organic phase (21 wt.%): Bis-GMA, UDMA, Bis-EMA; Inorganic phase (78 wt.%): 61 wt.% barium aluminium silicate glass, ytterbium fluoride, and spherical mixed oxide; 17 wt.% polymer fillers or isofillers; Photoinitiators: CQ and Ivocerin, stabilizers and pigments (<1.0 wt.%)
Low-viscosity Fast-curing Bulk-Fill Resin Composite (Shade IVA)	Tetric PowerFlow-Ivoclar Vivadent AG, Schaan, Liechtenstein (Z05Y55)	Organic Phase (28 wt.%): Bis-GMA, Bis-EMA, DCP, PCPEG-MA; Inorganic Phase (71 wt.%): barium aluminium silicate glass, an Isofiller (glass filler and ytterbium fluoride); Photoinitiators: CQ, Ivocerin, and TPO; Additives and Pigments (<1 wt.%).

High-viscosity Fast-curing Bulk-Fill Resin Composite (shade IVA)	Tetric PowerFill - Ivoclar Vivadent AG, Liechtenstein (Z05S0R)	Organic phase (18 wt.%): Bis-GMA, UDMA, Bis-EMA, TCDDMA, propoxylated bisphenol A dimethacrylate, DCP and an AFCT agent; Inorganic phase (79 wt.%): barium aluminium silicate glass, an isofiller (glass filler and ytterbium fluoride), and a spherical mixed oxide; Photoinitiators: CQ, Ivocerin, and TPO; Additives and pigments (3 wt.%)
LED LCU	Bluephase Powercure - Ivoclar Vivadent AG, Schaan, Liechtenstein (SN 1428023109)	Multi-wave LED Operating modes: Cure 3s Pre-Cure 2s High Power 10, 15, 20s Turbo 5s
LED LCU	Quazar - FGM, Joinville, SC, Brazil (SN L23A1021R)	Multi-wave LED Operating modes: Normal 5, 10, 15, 20s High 3, 5s Turbo 1, 3s Ortho 3X5, 3X10s Soft 5, 10, 15, 20s Pulse 5, 10, 15, 20s Check 30, 60s

* According to the manufacturers

Bis-GMA: bisphenol-A-diglycidyl dimethacrylate; **Bis-EMA**: bisphenol-A-polyethyleneglycol diether dimethacrylate; **UDMA**: urethane dimethacrylate. **TCDDMA**: tricyclodecane dimethanol dimethacrylate; **CQ**: camphorquinone; **AFCT**: β-allyl sulfone addition-fragmentation chain transfer; **TPO**: 2,4,6-trimethylbenzoyldiphenylphosphine oxide; **DCP**: tricyclodecane-dimethanol dimethacrylate; **PCPEG-MA**: Polycarbonate Poly(ethylene glycol) Methacrylate.

Table 2. Mean and standard deviation of radiant power (mW), irradiance (mW/cm²), and radiant exposure (J/cm²) of the two light-curing units used in two different curing modes, with and without the matrix.

Curing modes		**Power (mW)**		**Irradiance (mW/cm²)**		**Radiant exposure (J/cm²)**	
	Internal Tip Diameter (mm)	**No Matrix**	**Matrix**	**No Matrix**	**Matrix**	**No Matrix**	**Matrix**
Quazar - 20s	9,9	1109 ± 3.5	484 ± 3.1	1440 ± 4.6	629 ± 4.0	28.8 ± 0.09	12.6 ± 0.08
Quazar - 3s	9,9	2689 ± 3.2	1167 ± 3.7	3494 ± 4.2	1516 ± 4.9	10.5 ± 0.01	4.5 ± 0.01
Bluephase - 20s	8,2	729 ± 0.8	410 ± 1.0	1381 ±1.5	776 ± 2.0	27.6 ± 0.03	15.5 ± 0.04
Bluephase - 3s	8,2	1893 ± 1.6	1079 ± 2.6	3585 ± 2.9	2043 ± 4.9	10.8 ± 0.01	6.1 ± 0.01

Table 3. Mean and standard deviation of microhardness depth of cure in each region with both LCUs.

LED	Resin	Region	Depth				
			0.5mm	1mm	2mm	3mm	4mm
Bluephase PowerCure	PowerFill	Mesial	68.2 (0.8)	65.8 (0.5)	63.8 (0.7)	61.9 (0.6)	59.1 (0.8)
		Center	68.4 (0.9)	66.2 (0.6)	63.9 (0.7)	61.8 (0.4)	58.7 (0.9)
		Distal	68.8 (1.0)	66.1 (0.7)	63.7 (0.7)	61.9 (0.6)	58.5 (1.0)
	PowerFill + PowerFlow	Mesial	68.8 (0.6)	65.4 (0.9)	54.9 (1.5)	51.2 (0.7)	46.0 (1.6)
		Center	68.5 (0.8)	66.2 (1.4)	54.5 (0.7)	51.0 (0.8)	47.5 (1.1)
		Distal	69.2 (0.7)	65.5 (0.6)	54.7 (1.0)	51.1 (0.6)	47.0 (1.0)
	Tetric	Mesial	69.4 (1.0)	65.9 (0.7)	63.8 (0.7)	61.8 (0.8)	57.3 (1.6)
		Center	68.6 (1.0)	65.7 (0.7)	63.7 (0.7)	61.7 (0.7)	56.7 (1.4)
		Distal	69.3 (0.8)	65.9 (0.6)	63.7 (0.7)	61.9 (0.6)	56.6 (1.5)
	Tetric + TetricFlow	Mesial	69.1 (0.6)	65.6 (0.4)	55.3 (0.7)	51.6 (0.6)	47.0 (1.5)
		Center	68.8 (0.9)	65.9 (1.6)	54.9 (1.5)	51.3 (0.7)	46.0 (1.6)
		Distal	69.1 (1.0)	65.7 (0.6)	54.5 (0.7)	51.2 (0.7)	47.5 (1.1)
Quazar	PowerFill	Mesial	68.3 (0.7)	65.8 (0.6)	63.8 (0.7)	61.6 (0.5)	58.8 (0.7)
		Center	68.3 (0.7)	66.1 (0.5)	64.0 (0.8)	61.8 (0.7)	58.7 (0.7)
		Distal	68.8 (0.7)	66.0 (0.5)	64.1 (0.7)	62.2 (0.5)	58.7 (0.7)
	PowerFill + PowerFlow	Mesial	68.8 (1.0)	65.6 (1.0)	53.2 (0.5)	50.7 (0.8)	46.7 (1.6)
		Center	68.5 (0.9)	66.1 (1.5)	53.5 (0.4)	50.5 (0.4)	47.9 (1.4)
		Distal	68.7 (0.9)	65.8 (0.9)	53.3 (0.5)	50.5 (0.4)	46.6 (1.6)
	Tetric	Mesial	69.1 (0.9)	65.5 (0.4)	63.8 (0.8)	61.3 (0.9)	56.6 (1.2)
		Center	69.4 (1.0)	65.5 (0.7)	63.8 (0.8)	61.3 (0.7)	56.6 (1.0)
		Distal	69.0 (0.7)	65.9 (0.4)	63.8 (0.8)	61.9 (0.7)	57.0 (1.2)
	Tetric + TetricFlow	Mesial	69.2 (0.8)	66.1 (0.6)	53.9 (0.8)	51.6 (0.7)	46.6 (1.7)
		Center	69.1 (0.8)	66.1 (0.6)	53.8 (1.0)	51.1 (0.8)	47.7 (1.6)
		Distal	69.4 (0.5)	66.0 (0.5)	53.6 (0.7)	50.8 (0.8)	47.3 (1.3)

Statistical significance was obsrerved for the factors depth ($p<0.001$) and resin ($p<0.001$), but not for region ($p=0.283$) and LCU ($p=0.174$); Statistical significance was observed for the interaction between depth and resin ($p<0.001$), but not for depth × resin × region ($p=0.065$), depth × region × LCU ($p=0.373$), and depth × resin × region × LCU ($p=0.774$) – Repeated-measures ANOVA Test ($\alpha=5\%$).

Figures

Figure 1. Printed matrix with an aperture of the same dimensions as the MOD cavity of the samples (3mm wide x 6mm long) and with different thicknesses (1, 3, and 4mm) for light transmission through the resin.

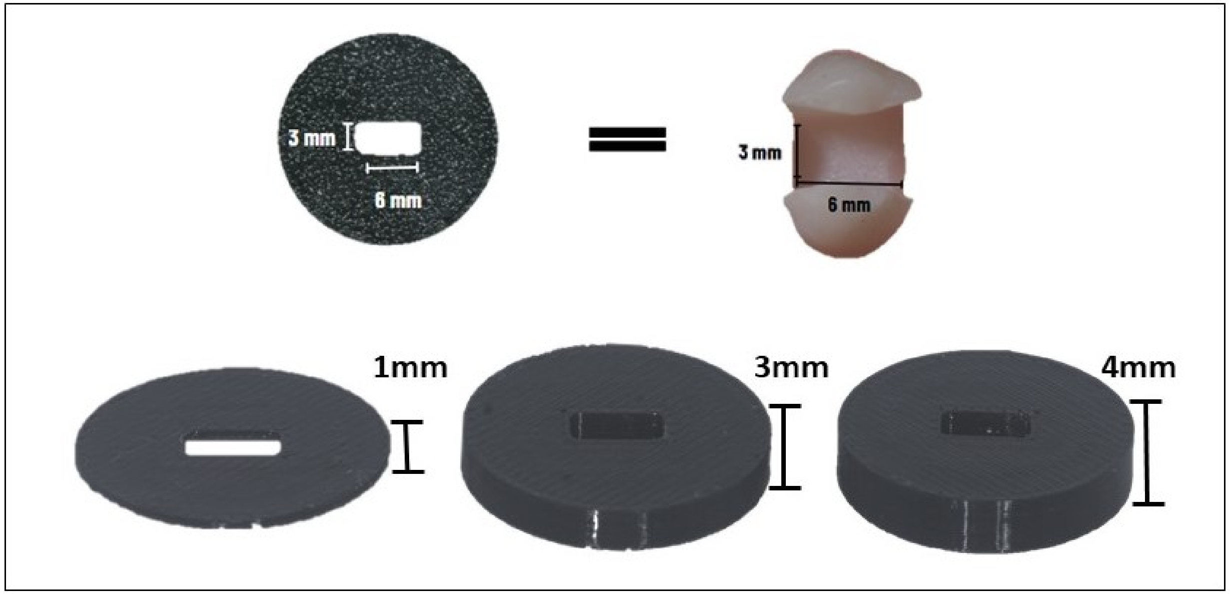


Figure 2. Two and three-dimensional irradiance profiles of the LCUs in both curing modes. These figures show the tip diameter and irradiance (mW/cm²) with no matrix.

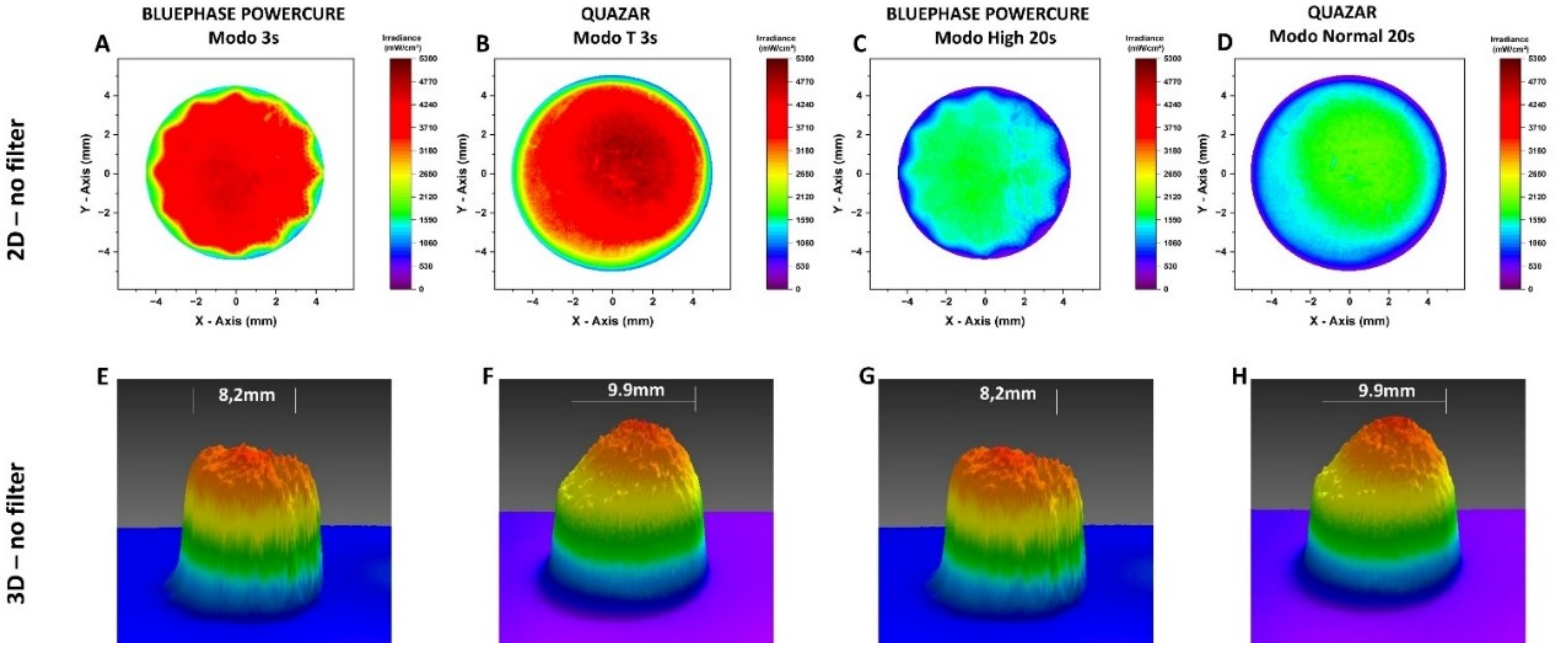


Figure 3. Two and three-dimensional images of the light beam profile from both LCUs in the two curing modes through different thicknesses of resins.

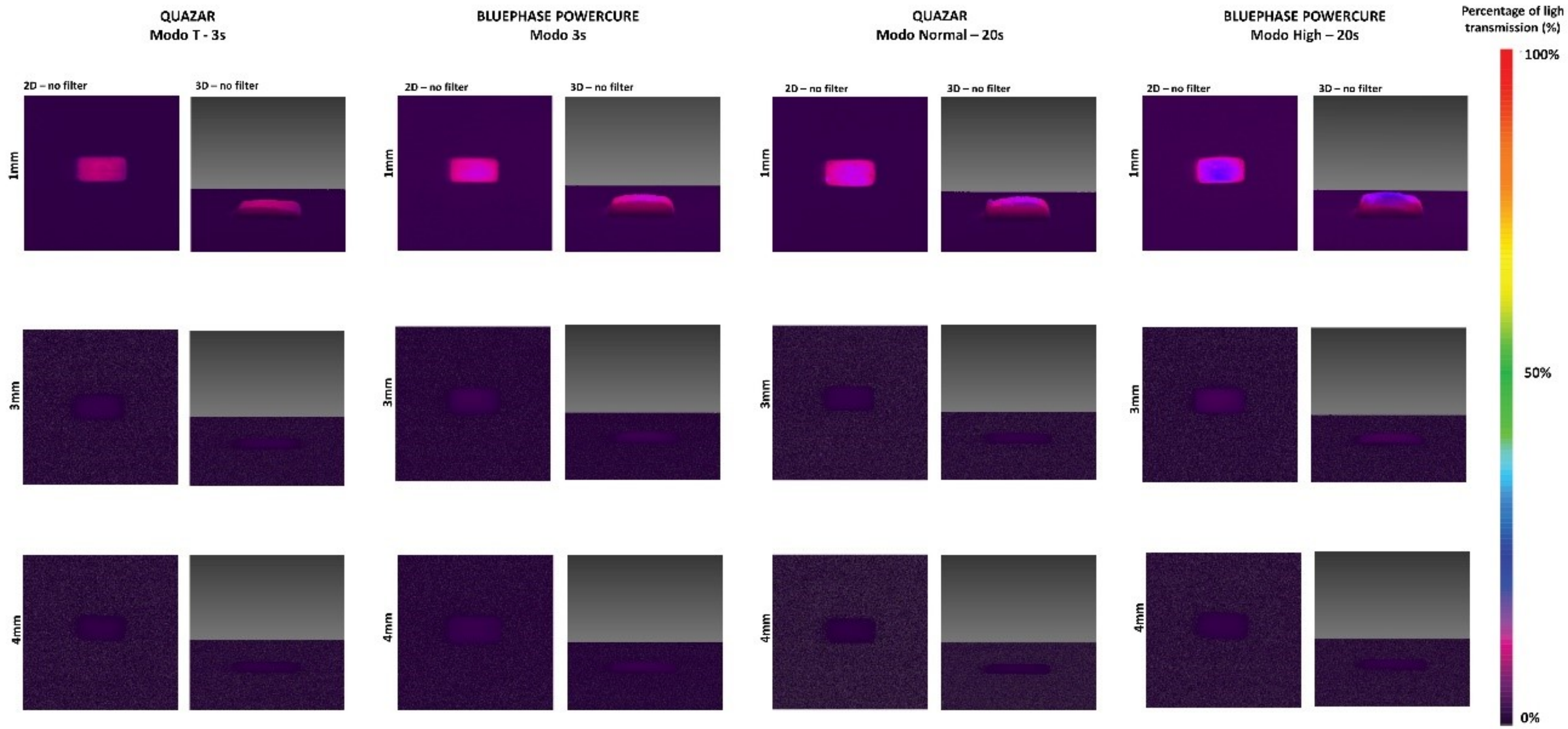


Figure 4. Emission spectra, power, and irradiance of the LCUs in their standard (20s) and high (3s) modes with no matrix.

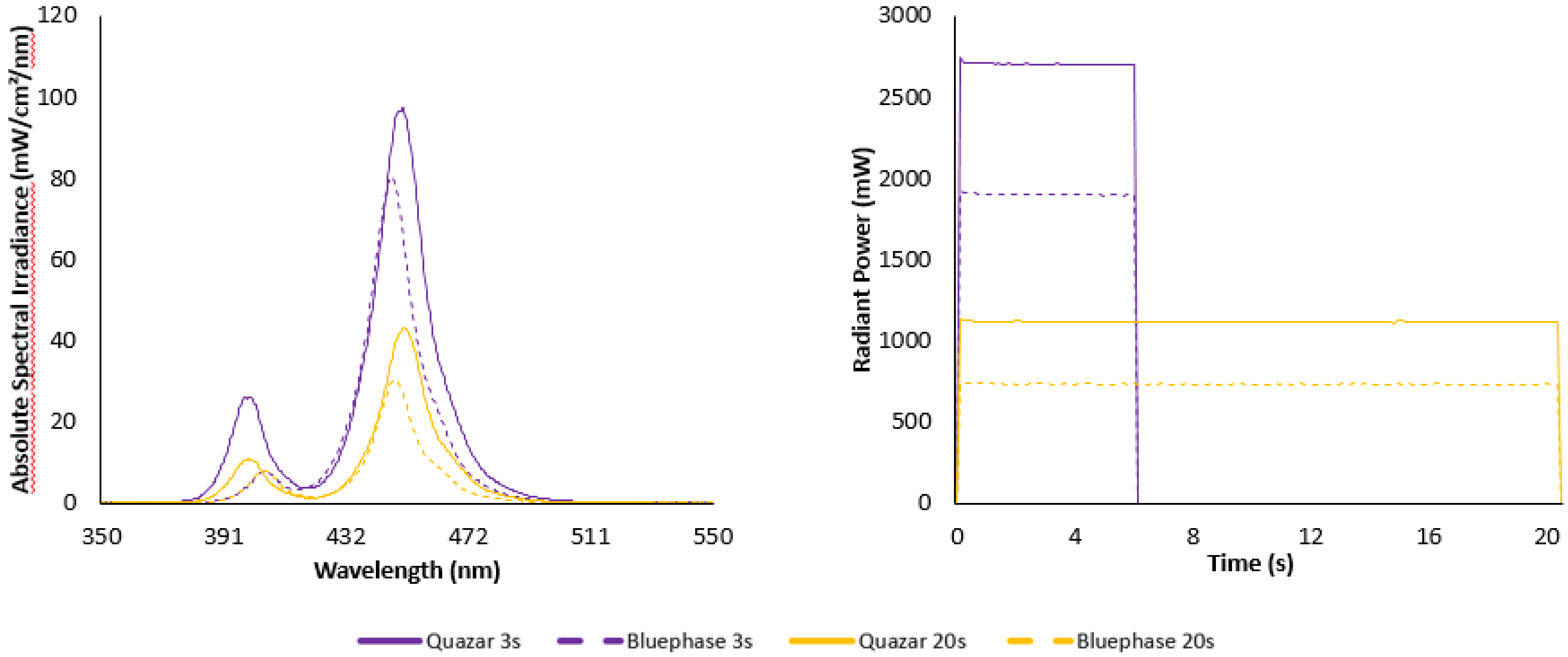


Figure 5. Emission spectra, power, and irradiance of the LCUs in higher (3s) modes, through the matrix without no resin composite and with resin composite at 1, 3, and 4mm-depth.

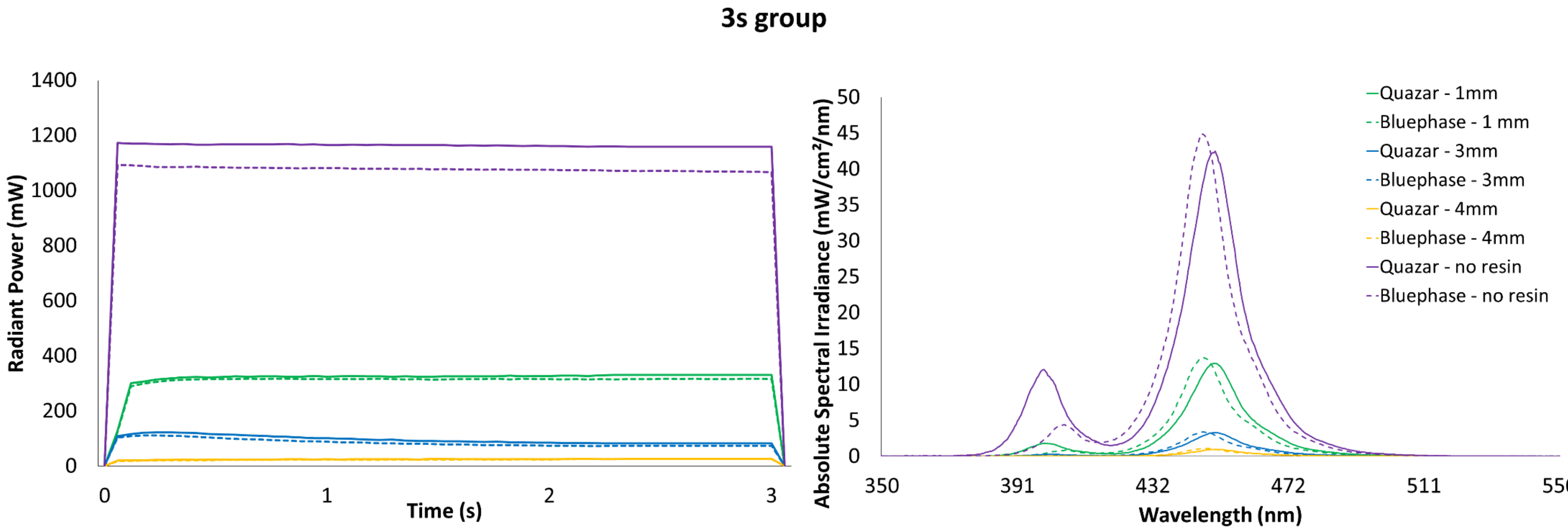


Figure 6. Emission spectra, power, and irradiance of the LCUs in higher (20s) modes, through the matrix without no resin composite and with resin composite at 1, 3, and 4mm-depth.

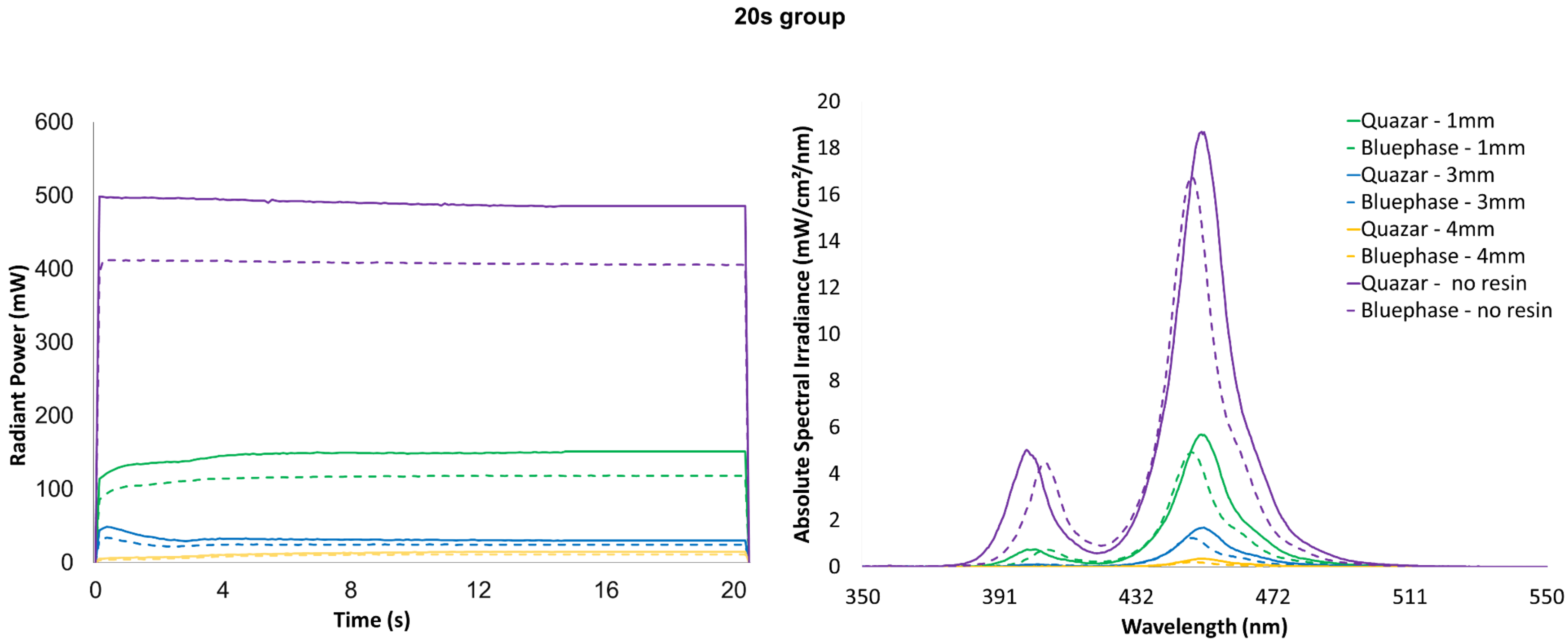
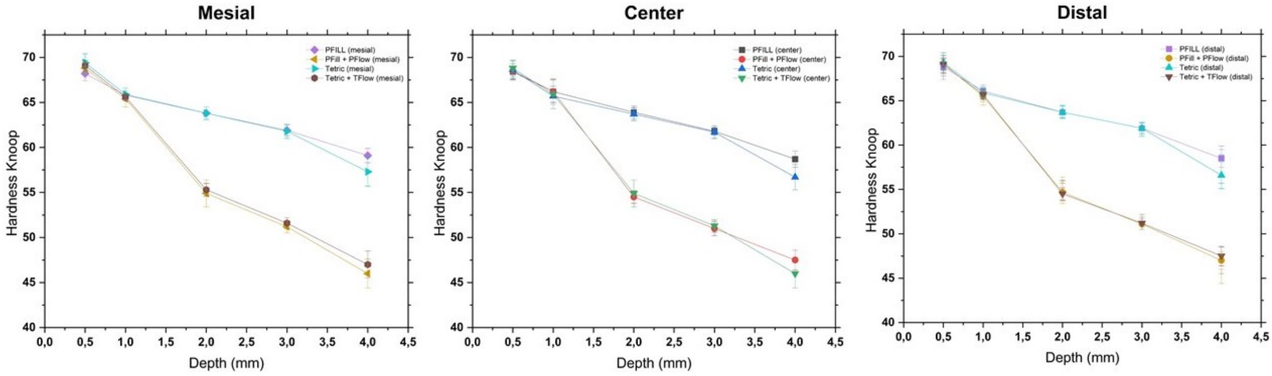
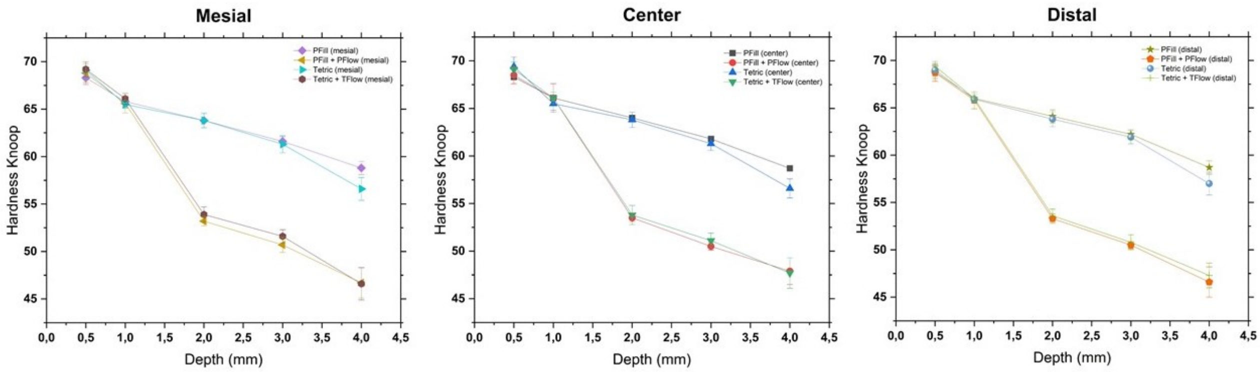


Figure 7. Mean and standard deviation of the regional depth of cure (microhardness) of the resin composites with different light-curing techniques.

Bluephase Powercure



Quazar



4. CONCLUSÕES

Dentro das limitações do presente trabalho, conclui-se que:

- A trasnmissão da luz foi atenuada conforme aumento da espessura do material;
- A região do preparo cavitário (mesial, central e distal) não apresentou influência na microdureza das resinas compostas;
- As fontes de luz não influenciaram na microdureza dos compósitos;
- Não foi observada diferença significativa entre os modos de fotopolimerização;
- As resinas de baixa viscosidade apresentaram menores valores de microdureza quando comparadas com as resinas de alta viscosidade;
- A profundidade de polimerização influenciou na dureza dos materiais, mas a razão de dureza base/superfície atingiu pelo menos 80%, portanto uma adequada polimerização foi alcançada.

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