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Monowave vs. Polywave Light – Curing Units: Effect on Light Transmission of Composite without Alternative Photoinitiators

Jednovalni vs. viševalni fotopolimerizacijski uređaji: utjecaj na transmisiju svjetlosti kompozita bez alternativnih fotoinicijatora

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Abstract

Objective: The aim of this study was to compare the light transmission of monowave and polywave-curing devices by a bulk-fill composite containing only camphorquinone as a photoinitiator. **Materials and methods:** Three light-curing devices were used to cure bulk-fill composite QuiXfil: one monowave (Translux® Wave) and two polywave (VALO Cordless and Bluephase® PowerCure). The NIST-calibrated spectrometer (MARC Resin Calibrator, BlueLight Analytics Inc.) was used to measure the incident and transmitted light through a 2-mm composite specimen over 20 s. Light transmittance was calculated from the ratio of the amount of transmitted and incident light. For data analysis (ANOVA, $\alpha = 0.05$), total irradiation of the entire spectrum, irradiation with wavelengths of 360-420 nm for the violet spectrum, and 420-540 nm for the blue spectrum were selected. **Results:** Monowave curing unit Translux® Wave had the lowest light transmission (13.78 ± 0.5%), similar to the violet light transmission of polywave devices (12.02 ± 0.94% and 13.81 ± 1.72% for Valo Cordless and Bluephase PowerCure, respectively). Blue light transmittance (32.15-23.70%) was more than twofold higher than for the wavelengths in the violet region of the spectrum (13.81-12.02%) for the two polywave devices. VALO Cordless showed the highest total and blue light transmission ($p<0.001$). There was no significant difference in the transmission of the violet part of the spectrum between VALO Cordless and Bluephase® PowerCure ($p = 0.465$). **Conclusion:** Within the limitations of this study, we could conclude that polywave curing devices can be used for the polymerization of the bulk-fill composite with camphorquinone as the sole photoinitiator.

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Introduction

Although resin composite materials have been used in dentistry for many years, their composition is constantly being modified and the light-curing units (LCU) improved to achieve the best possible clinical results while speeding up the restorative process (1).

One of the most important changes in composite materials concerns the photoinitiator system. Camphorquinone with a light absorption maximum at 468 nm wavelength is still the most common photoinitiator in composite materials (2). As a Norrish type II photoinitiator, camphorquinone requires a hydrogen donor, usually from the amine group, in order to be activated and form free radical species. The radical species subsequently initiate the polymerization reaction (3, 4). However, due to the intense yellow coloration,

Uvod

Iako se smolasti kompozitni materijali koriste u stomatologiji već niz godina, njihov sastav stalno se modificira, a fotopolimerizacijski uređaji (FPU) poboljšavaju kako bi se postigli najbolji mogući klinički rezultati uz ubrzavanje restaurativnoga procesa (1).

Jedna od najvažnijih promjena u kompozitnim materijalima odnosi se na sustav fotoinicijatora. Najčešći u kompozitnim materijalima i dalje je kamforkinon s maksimumom apsorpcije svjetlosti na valnoj duljini od 468 nm (2). Kao Norrish tip II fotoinicijator, kamforkinon zahtijeva donora vodika, obično iz amino skupine, da bi se aktivirao i formirao slobodne radikale. Radikalne vrste tada počinju reakcijom polimerizacije (3, 4). Međutim, zbog intenzivnog žutog obojenja kamforkinon je djelomično zamijenjen ili dopunjen camphorquinone has been partially replaced or supplemented by alternative photoinitiators to achieve lighter composite shades (5). The alternative photoinitiators such as the monoacylphosphine oxide, Lucirin-TPO or derivatives of dibenzoylgermanium (Ivocerin) belong to Norrish Type I photoinitiators and have the absorption maxima in the violet part of the spectrum (6, 7). Norrish Type I photoinitiators cleave after light irradiation and form two radicals that usually remain incorporated into the polymer network, therefore showing an increased quantum yield. As highly reactive photoinitiators, they are often used in bulk-fill composite materials to boost their depth of cure. For this reason, LCUs that deliver light at two or more different wavelengths, colloquially named polywave, are becoming increasingly prevalent on the market to allow adequate activation of type I photoinitiators at shorter wavelengths as well as camphorquinone (7), with the aim of achieving the highest possible degree of conversion. In addition, recently launched curing devices increase the radiant exitance over 3000 mW/cm^2 to polymerize the latest generation of fast curing bulk-fill composite material that polymerize in 3 s at 3000 mW/cm^2 (1, 4, 8).

However, the curing light is attenuated with the distance to the surface of the composite material (5). According to the Beer-Lambert law, the light attenuation is even higher when the light penetrates through the composite material and increases with the thickness of the composite layer (9). Due to the lower light transmission in the deepest areas of the composite layer and the lower activation of the photoinitiators, the degree of conversion is uneven, being highest at the surface of the material and decreasing in the deeper areas (10-12).

The light from the violet-blue region of the spectrum delivered to the surface of the composite material is attenuated by the reflection, absorption and scattering of the light energy that penetrates the material, thus causing the light intensity to decrease exponentially with the thickness of the material. The transmission of light through the material is partly diffuse and partly straight (6, 13). The absorption of light depends on the absorption coefficient of the photoinitiators, pigments and opaquers. At the same time, the scattering depends on the size and load of the filler particles and the wavelength of the emitted light. The refractive index of filler particles and the resin and the difference between their indices have a major influence on the transmission. A close match between the refractive indices of the filler and the matrix improves light transmission (14).

A better understanding of the light transmission of composites has led to the development of bulk-fill composites, thanks to which an adequate polymerization can be achieved in layers thicker than 2 mm (15). Some manufacturers point to the possibility of applying the material in a thickness of 4-5 mm (14). The first dental bulk-fill composite material was QuiXFil (Dentsply Sirona, North Carolina, USA). It was developed in 2003 for placement in 4-mm increments with a curing time of 20 s at 500-800 mW/cm^2 , and 10 s with a curing time of more than 800 mW/cm^2. The 20-year clinical follow-up showed that QuiXfil was as effective as the conventional nano-hybrid composite in Class I and Class II restora-

alternativnim fotoinicijatorima za postizanje svjetlijih kompozitnih nijansi (5). Alternativni fotoinicijatori, kao što su monoacilfosfin oksid, Lucirin-TPO ili derivati dibenzoilgermanija (Ivocerin), pripadaju Norrish tipu I fotoinicijatora i imaju maksimume apsorpcije u ljubičastom dijelu spektra (6, 7). Norrish tip I fotoinicijatori cijepaju se poslije svjetlosnog zračenja i formiraju dva radikala koji obično ostaju ugrađeni u polimernu mrežu, pokazujući stoga povećani kvantni prinos. Kao visokoreaktivni fotoinicijatori, često se koriste u *bulk-fill* kompozitnim materijalima kako bi se povećala njihova debljina polimerizacije. Zbog toga na tržištu sve više prevladavaju FPU-i koji isporučuju svjetlost na dvije ili više različitih valnih duljina, kolokvijalno nazvani viševalni, kako bi se omogućila odgovarajuća aktivacija fotoinicijatora tipa I na kraćim valnim duljinama, kao i kamforkinona (7), sa svrhom postizanja najvećega mogućeg stupnja konverzije. Osim toga, nedavno lansirani uređaji za polimerizaciju povećavaju izlazni intenzitet zračenja preko 3000 mW/cm^2 kako bi polimerizirali najnoviju generaciju brzo stvrdnjavajućih kompozitnih materijala koji polimeriziraju u 3 sekunde na 3000 mW/cm^2 (1, 4, 8).

Međutim, polimerizacijsko svjetlo slabi s udaljenošću od površine kompozitnog materijala (5). Prema Beer-Lambertovu zakonu, slabljenje svjetlosti još je veće kada svjetlost prodire kroz kompozitni materijal i povećava se s debljinom kompozitnog sloja (9). Zbog manje transmisije svjetlosti u najdubljim područjima kompozitnog sloja i slabije aktivacije fotoinicijatora, stupanj konverzije je neujednačen – najveći je na površini materijala, a smanjuje se u dubljim područjima (10 – 12).

Svjetlost iz ljubičasto-plavog područja spektra koja se isporučuje na površinu kompozitnog materijala prigušena je refleksijom, apsorpcijom i raspršenjem svjetlosne energije koja prodire kroz materijal i uzrokuje eksponencijalno smanjenje intenziteta svjetlosti s debljinom materijala. Transmisija svjetlosti kroz materijal dijelom je difuzna, a dijelom ravnomjerna (6, 13). Apsorpcija svjetlosti ovisi o koeficijentu apsorpcije fotoinicijatora, pigmenata i opakera. Istodobno, raspršenje ovisi o veličini i opterećenju čestica punila te valnoj duljini emitirane svjetlosti. Indeks loma svjetlosti pri prolasku kroz čestice punila i smole te razlika između njihovih indeksa ima velik utjecaj na transmisiju. Blisko podudaranje između indeksa loma punila i matrice poboljšava prijenos svjetlosti (14).

Bolje razumijevanje transmisije svjetlosti kod kompozitnih materijala rezultiralo je razvojem *bulk-fill* kompozita, zahvaljujući kojima se može postići odgovarajuća polimerizacija u slojevima debljima od 2 mm (15). Neki proizvođači navode mogućnost nanošenja materijala u debljini od 4 do 5 mm (14). Prvi dentalni *bulk-fill* kompozitni materijal QuiXFil (Dentsply Sirona, Sjeverna Karolina, SAD), razvijen je 2003. za postavljanje u slojevima od 4 mm s vremenom polimerizacije od 20 sekunda pri 500 do 800 mW/cm^2 i 10 sekunda kada se polimerizira na više od 800 mW/cm^2. Desetogodišnje kliničko praćenje pokazalo je da je QuiXfil bio jednako učinkovit kao i konvencionalni nanohibridni kompozit u restauracijama klase I i klase II (16). To je razmjerno dobro proučen kompozitni materijal na bazi uretan-dimetations (16). This is a relatively well-studied urethane dimethacrylate (UDMA)-based composite that uses camphorquinone as a photoinitiator.

Polywave LCUs are considered necessary for the light-curing of composites containing alternative photoinitiators, but they are not necessary for composites based only on camphorquinone. However, it is not economical to have multiple LCUs for different materials in a dental practice. Since the polywave LCUs have a broader spectrum, it is practical to have one LCU for all purposes. With polywave LCUs, one of the blue LEDs is usually replaced by the violet LED, which reduces the radiant output in the blue part of the spectrum compared to exclusively blue light LCUs. In addition, the positioning of the violet and blue LEDs can lead to an inhomogeneous spectral output over the irradiated area (5, 17, 18). Since the violet LEDs generally have a lower irradiance, insufficient homogenization of the light output may result in insufficient curing of the parts of the composite restoration illuminated by the predominantly violet light (19, 20). This fact could have a negative effect on the light transmission and ultimately on the degree of conversion of composites without alternative photoinitiators. The aim of this study was, therefore, to investigate the influence of polywave LCUs on the light transmission of the composite containing only camphorquinone as a photoinitiator. The null hypothesis was that there would be no difference in the light transmission of monowave and polywave LCUs in the composite material without the alternative photoinitiators.

Materials and methods

Characterization of the light curing units

Three LCUs were selected for this study:

(I) VALO™ Cordless (Ultradent, South Jordan, USA; VC) as a representative of the three-peak LCU

(II) Bluephase® PowerCure (Ivoclar Vivadent, Schaan, Liechtenstein; BPC) as a representative of the two-peak LCU

(III) Translux® Wave (Kulzer GmbH, Hanau, Germany; TW) as a representative of the one-peak LCU.

The LCUs were used in standard modes with a nominal irradiance in the range 1000-1200 mW/cm^2: High power mode for BPC, Standard mode for VC and TW had a single curing mode.

The LCUs were characterized using a National Institute of Standards and Technology (NIST)-referenced and calibrated spectrometer MARC™ System (Bluelight Analytics Inc., Halifax, NS, Canada). Radiant exitance of LCUs was measured at an empty compartment in triplicate.

Light transmission

Light transmission was measured in real time through the bulk-fill composite QuiXFil. According to the manufacturer QuiXFil contains 86% wt%/66% vol% filler load with the resin consisting of UDMA, triethylene glycol dimethacrylate, di- and trimethacrylate resins, carboxylic acid-modified dimethacrylate resin and butylated hydroxytoluene. It also contains a UV stabilizer as well as camphorquinone and ethyl 4(dimethylamino) benzoate as a photoinitiator system.

krilata (UDMA) koji se koristi kamforkinonom kao fotoinicijatorom.

Viševalni FPU-i smatraju se nužnima za svjetlosnu polimerizaciju kompozita koji sadrže alternativne fotoinicijatore, ali nisu nužni za kompozite temeljene samo na kamforkinonu. Međutim, nije ekonomično imati više FPU-a za različite materijale u stomatološkoj ordinaciji. Budući da viševalni FPU-i imaju širi spektar, razborito je imati jedan FPU za sve namjene. Kod viševalnih FPU-a, jedna od plavih LED dioda obično se zamjenjuje ljubičastom LED diodom, što smanjuje izlazno zračenje u plavom dijelu spektra u usporedbi s FPU-ima s isključivo plavim svjetlom. Osim toga, pozicioniranje ljubičaste i plave LED diode može dovesti do nehomogenoga spektralnog snopa (5, 17, 18). Budući da ljubičaste LED diode općenito imaju manji intenzitet zračenja svjetlosti, nedovoljna homogenizacija svjetlosnoga snopa može rezultirati nedovoljnom polimerizacijom dijelova kompozitne restauracije osvijetljenih pretežno ljubičastim svjetlom (19, 20). Ta bi činjenica mogla negativno utjecati na transmisiju svjetlosti i u konačnici na stupanj konverzije kompozita bez alternativnih fotoinicijatora. Stoga je cilj ove studije bio istražiti utjecaj viševalnih FPU-a na prijenos svjetlosti kompozita koji sadrži samo kamforkinon kao fotoinicijator. Nulta hipoteza bila je da nema razlike u prijenosu svjetlosti jednovalnih i viševalnih FPU-a u kompozitnom materijalu bez alternativnih fotoinicijatora.

Materijali i metode

Karakterizacija fotopolimerizacijskih uređaja

Za ovu studiju odabrana su tri FPU-a:

(I) VALO™ Cordless (Ultradent, Južni Jordan, SAD; VC) kao predstavnik FPU-a s tri vrha

(II) Bluephase® PowerCure (Ivoclar Vivadent, Schaan, Lihtenštajn; BPC) kao predstavnik FPU-a s dva vrha

(III) Translux® Wave (Kulzer GmbH, Hanau, Njemačka; TW) kao predstavnik FPU-a s jednim vrhom.

FPU-i su korišteni u standardnom načinu rada s nominalnim zračenjem u rasponu od 1000 do 1200 mW/cm^2: u načinu rada visokog intenziteta za BPC, standardni način rada za VC i TW koji je imao jedan način stvrdnjavanja.

FPU-i su okarakterizirani korištenjem sustava MARC™ spektrometra koji je referiran i kalibriran u Nacionalnom institutu za standarde i tehnologiju (NIST) (Bluelight Analytics Inc., Halifax, NS, Kanada). Izlazno zračenje FPU-a izmjereno je u praznom odjeljku u tri ponavljanja.

Transmisija svjetlosti

Transmisija svjetlosti mjerena je u stvarnom vremenu kroz *bulk fill* kompozit QuiXFil. Prema proizvođaču, QuiXFil sadrži 86 % mas %/66 % vol % punila sa smolom koja se sastoji od UDMA-e, trietilen glikol dimetakrilata, dimetakrilatnih i trimetakrilatnih smola, dimetakrilatne smole modificirane karboksilnom kiselinom i butiliranog hidroksitoluena. Također sadrži UV stabilizator te kamforkinon i etil 4 (dimetilamino) benzoat kao fotoinicijatorski sustav.

Cylindrical Delrin® molds (h = 2 mm, d = 6 mm) were filled with uncured material. The upper and lower openings were covered with polyethylene terephthalate (PET) film and then pressed with a glass slide until the mold was in contact to remove the excess material. The glass slide was removed and the Delrin® mold with the uncured resin and PET sheets on both sides was placed on the sensor of the NIST calibrated spectrometer MARC™ Resin Calibrator (BlueLight Analytics Inc., Halifax, Canada). The composite samples (n = 6) were cured for 20 seconds with the tip of the LCU perpendicular and in direct contact with the top PET film on the uncured material. The position of the LCUs was controlled and fixed using the MARC™ Accessory bench (BlueLight Analytics Inc., Halifax, Canada). The data were recorded with the MARC™ software (BlueLight Analytics Inc., Halifax, Canada) on the MARC™ laptop (BlueLight Analytics Inc., Halifax, Canada).

The real-time irradiance at the bottom of the specimen at a distance of 2 mm was measured by the MARC™ Resin Calibrator over an illumination period of 20 s.

Irradiance and radiant exposure were recorded individually at a wavelength of 360–540 nm at a rate of 16 recordings/sec. The sensor was triggered at 50 mW. The radiant exposure was calculated by integrating the irradiance with the wavelength at the exposure time used (20 s). For data analysis, the total irradiance of the entire spectrum, the irradiance with wavelengths of 360-420 nm for the violet spectrum and 420-540 nm for the blue spectrum were selected.

Statistical analysis

Statistical analysis was performed using SPSS version 25.0 (IBM, Armonk, NY, USA). Despite slight deviations from normality as indicated by normal Q-Q plots, the parametric statistical analysis was used due to balanced size of experimental groups. Light transmittance values were compared among the curing units for the whole measured spectrum, and additionally for the blue and violet parts of the spectrum using one-way ANOVA using the Tukey post-hoc test for multiple comparisons. The overall level of significance was $\alpha = 0.05$.

Results

Characterization of curing units

One LCU, TW, exhibited a single peak in the blue spectral region and served as a monowave control, whereas BPC and VC exhibited an additional peak in the violet spectral region and were labeled as polywave. In addition, VC exhibited two peaks in the blue region, with maxima at 447 and 462 nm (Figure 1). In the above-mentioned standard curing modes used in this study for the three LCUs tested, TW exhibited the highest radiant exitance, followed by BPC and VC (Figure 2). The measured spectral and radiant properties of the curing units used in this study are listed in Table 2.

Light transmission

A 2 mm thick composite layer reduced the total light transmission in the 360-540 nm range to 13.78 ± 0.5%%

Cilindrični Delrin® kalupi (h = 2 mm, d = 6 mm) punjeni su nepolimeriziranim materijalom. Gornji i donji otvori prekriveni su polietilen-tereftalatnom (PET) folijom i zatim pritisnuti predmetnim stakalcem do kontakta s kalupom da bi se uklonio višak materijala. Stakalce je uklonjeno i Delrin® kalup s nepolimeriziranom kompozitnom smolom i PET folijama s obje strane postavljen je na senzor NIST kalibriranog spektrometra MARC™ Resin Calibratora (BlueLight Analytics Inc., Halifax, Kanada). Kompozitni uzorci (n = 6) polimerizirani su 20 sekunda s vrhom FPU-a okomito na i u izravnom kontaktu s gornjom PET folijom na nepolimeriziranom materijalu. Položaj FPU-a kontroliran je i fiksiran s pomoću MARC™ Accessory bencha (BlueLight Analytics Inc., Halifax, Kanada). Podatci su registrirani s pomoću softvera MARC™ (BlueLight Analytics Inc., Halifax, Kanada) na MARC™ prijenosnom računalu (BlueLight Analytics Inc., Halifax, Kanada).

Zračenje u stvarnom vremenu na dnu uzorka na udaljenosti od 2 mm izmjereno je MARC™ Resin Calibratorom tijekom razdoblja osvjetljenja od 20 sekunda.

Vrijednosti intenziteta svjetlosti i izloženosti zračenju zabilježene su pojedinačno na valnoj duljini od 360 do 540 nm brzinom od 16 snimaka/sekundi. Senzor je bio aktiviran na 50 mW. Izloženost zračenju izračunata je integracijom intenziteta s valnom duljinom u upotrjebljenom vremenu izlaganja (20 s). Za analizu podataka odabrano je ukupno zračenje cijelog spektra, zračenje valnih duljina od 360 do 420 nm za ljubičasti spektar i od 420 do 540 nm za plavi spektar.

Statistička analiza

Statistička analiza provedena je u SPSS verziji 25.0 (IBM, Armonk, NY, SAD). Unatoč neznatnim odstupanjima od normalnosti kako pokazuju normalni Q-Q dijagrami, korištena je parametarska statistička analiza zbog uravnoteženosti veličine eksperimentalnih skupina. Vrijednosti transmisije svjetla uspoređene su među FPU-ima za cijeli mjereni spektar, te dodatno za plave i ljubičaste dijelove spektra korištenjem jednosmjerne ANOVA-e s Tukeyjevim post-hoc testom za višestruke usporedbe. Ukupna razina značajnosti bila je $\alpha = 0{,}05$.

Rezultati

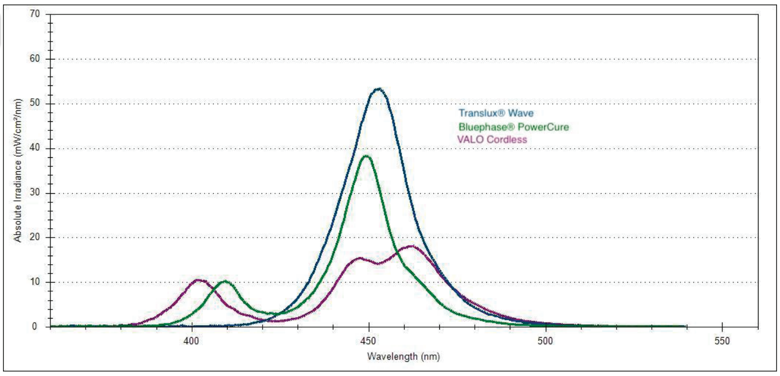
Karakterizacija polimerizacijskih uređaja

Jedan FPU, TW, pokazao je jedan vrh u plavom području spektra i poslužio je kao jednovalna kontrola, a BPC i VC pokazali su vrh u ljubičastom području spektra i označeni su kao viševalni. Uz to, VC je pokazao dva vrha u plavom području spektra, s maksimumima na 447 i 462 nm (slika 1.). U gore spomenutim standardnim načinima polimerizacije koji su rabljeni u ovoj studiji za tri testirana FPU-a, TW je pokazao najveću izlaznu vrijednost emitiranog zračenja, a slijede ga BPC i VC (slika 2.). Izmjerena spektralna svojstva i svojstva zračenja polimerizacijskih uređaja korištenih u ovoj studiji navedena su u tablici 2.

Transmisija svjetlosti

Kompozitni sloj debljine 2 mm smanjio je ukupnu transmisiju svjetlosti u rasponu od 360 do 540 nm na 13,78 ±

1



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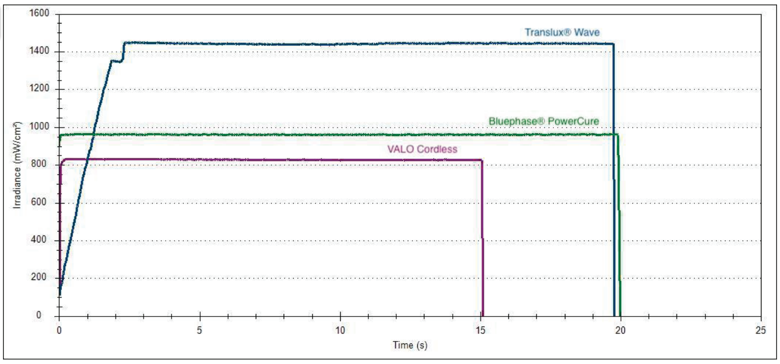

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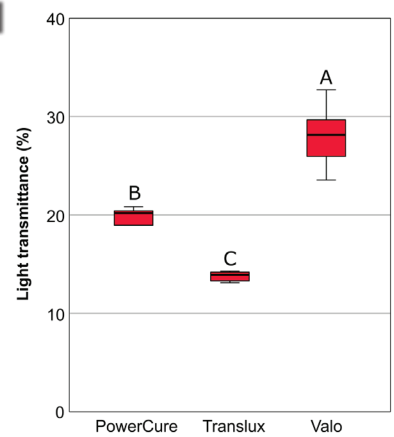

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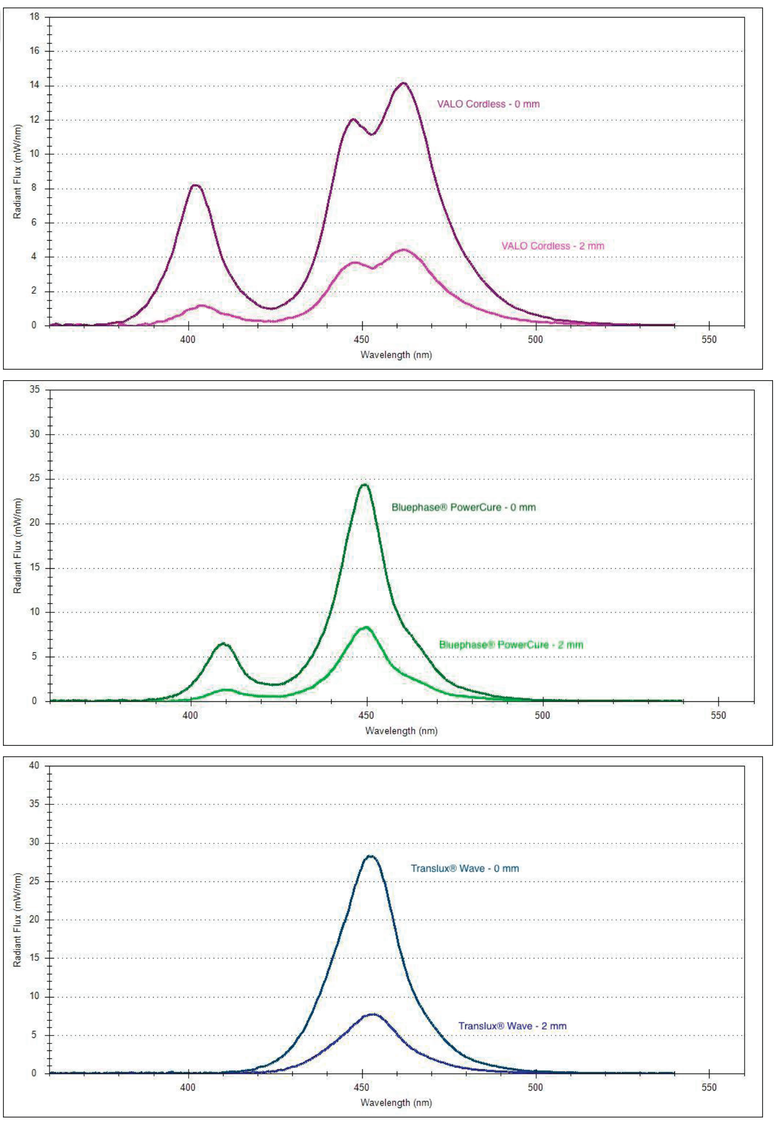


Figure 1 Spectral emission of the light-curing units used in the study. Blue line – Translux Wave, green line – Bluephase PowerCure, purple line – Valo Cordless.

Slika 1. Spektralna emisija fotopolimerizacijskih uređaja rabljenih u ovom istraživanju; plava linija – Translux Wave, zelena linija – Bluephase PowerCure, ljubičasta linija – Valo Cordless

Figure 2 Radiant exitance as a function of time for the tested light-curing units. Translux Wave is characterized by the slow ascending irradiance during the first 3 seconds after activation.

Slika 2. Izlazno zračenje kao funkcija vremena za testirane fotopolimerizacijske uređaje; Translux Wave obilježava sporo uzlazno zračenje tijekom prve 3 sekunde nakon aktivacije

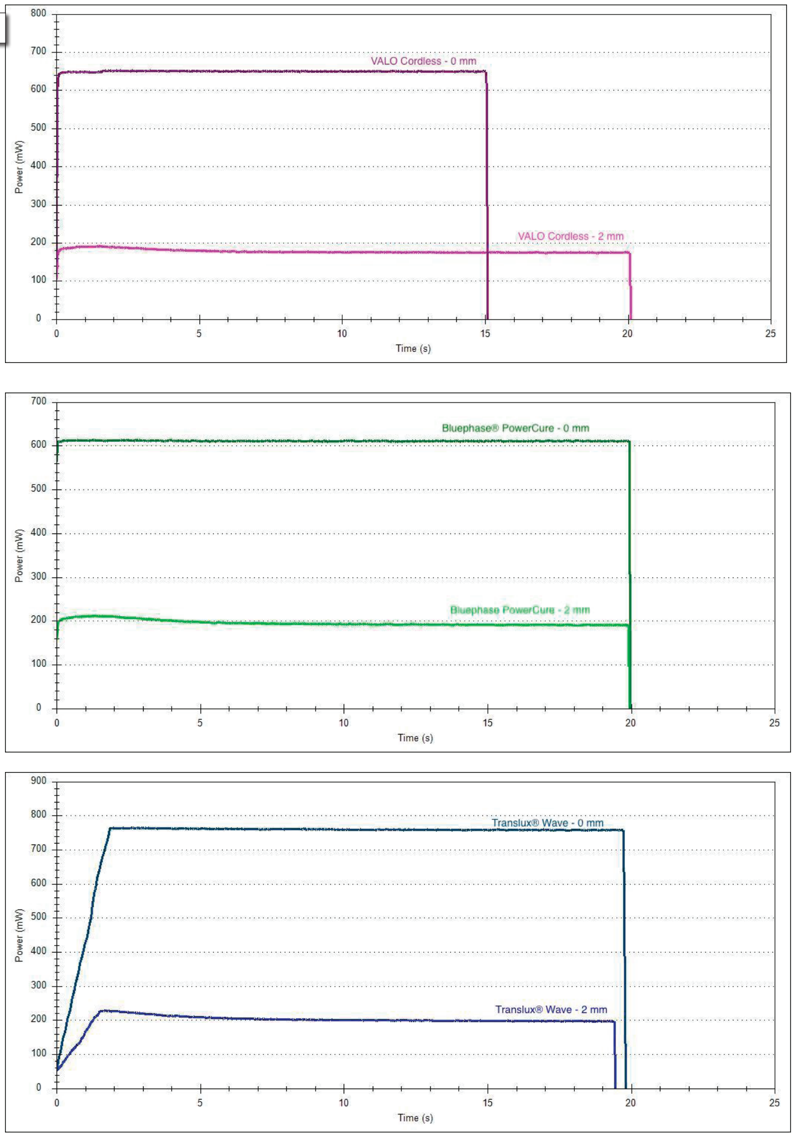
Figure 3 Total light transmittance in the area 360-540 nm of different curing units measured at a 2 mm depth of composite specimens. Identical letters denote statistically similar groups.

Slika 3. Ukupna transmisija svjetlosti u spektralnom području 360 – 540 nm različitih fotopolimerizacijskih uređaja izmjerena na 2 mm debljine kompozitnih uzoraka (identična slova označavaju statistički slične skupine)

Figure 4 Incident (0 mm) and transmitted radiant flux through 2 mm composite specimen of: A – VALO Cordless; B – Bluephase PowerCure and C- Translux Wave.

Slika 4. Upadni (0 mm) i propušteni tok zračenja kroz kompozitni uzorak od 2 mm: A – VALO Cordless; B – Bluephase PowerCure i C – Translux Wave

5



6

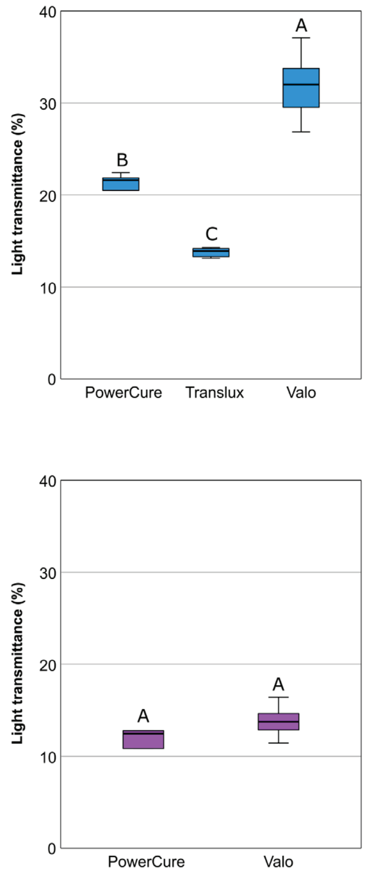


Figure 5 Incident (0 mm) and transmitted power through 2 mm composite specimen of: A – VALO Cordless; B – Bluephase PowerCure and C-Translux Wave.
Slika 5. Upadna (0 mm) i propuštena snaga zračenja kroz kompozitni uzorak od 2 mm: A – VALO Cordless; B – Bluephase PowerCure i C – Translux Wave
Figure 6 Light transmittance divided on the blue (A) blue (420-540 nm) and (B) violet spectral area (360-420 nm) of different curing units measured at a 2 mm depth of composite specimens. Identical letters denote statistically similar groups within each panel.
Slika 6. Transmisija svjetlosti podijeljena na (A) plavi (420 – 540 nm) i (B) ljubičasti dio spektra (360 – 420 nm) različitih fotopolimerizacijskih uređaja izmjerenih na 2 mm debljine kompozitnih uzoraka (identična slova označavaju statistički slične skupine unutar svakog panela)

Table 1 Spectral and radiant characteristics of the curing units used in this study as measured by the spectrometer MARCTM Resin Calibrator
Tablica 1 Spektralne karakteristike i karakteristike zračenja fotopolimerizacijskih uređaja korištenih u ovom istraživanju

Name (abbreviation) • Naziv (skraćenica)	Type of curing unit • Vrsta fotopolimerizacijskog uređaja	Peaks • Vrhovi			Mean irradiance at 0 mm (mW/cm²) • Srednja vrijednost intenziteta zračenja na 0 mm (mW/cm²)	Total energy from 360-540 nm (J/cm²) • Ukupna emitirana energija 360-540 nm (J/cm²)
		violet • ljubičasti	blue I • plavi I	blue II • plavi II		
VALO™ Cordless (VC)	polywave • viševalni	401 nm	447 nm	462 nm	824	12.44
Bluephase® PowerCure (BPC)	polywave • viševalni	409 nm	449 nm	/	958	19.15
Translux® Wave (TW)	monowave • jednovalni	/	453 nm	/	1372	27.15

for TW, 20.31 ± 0.79% for BPC and 28.03 ± 3.14% for VC of the original light emission of the respective curing units (Figures 3, 4 and 5). The values for total light transmittance were statistically different for each LCU ($p < 0.001$). The blue light transmittance was also lowest for the monowave LCU TW, followed by BPC and VC with the highest values ($p < 0.001$). When comparing the two polywave LCUs, the violet light transmission was reduced by a 2 mm thick layer to 12.02 ± 0.94% and 13.81 ± 1.71% for VC and BPC, respectively (Figure 6), with no statistical difference between them (p = 0,481 and p = 1.0 for BPC and VC, respectively).

Discussion

This study investigated the influence of polywave LCUs on the light transmission through a composite material containing camphorquinone as the sole photoinitiator and thus theoretically not requiring the violet part of the spectrum for adequate polymerization. The results showed that the light transmittance was improved for polywave LCUs compared to the control monowave LCU which had the lowest total light transmittance (in the range 360-540 nm) and the lowest blue light transmittance (420-540 nm). Therefore, the null hypothesis was rejected. We can deduct that there is no detrimental effect of the polywave curing units on light transmission through a 2-mm layer. As expected, the light transmittance is lower at violet wavelengths than at blue wavelengths.

The reduction in light transmission can be attributed at least in part to absorption of photons by the photoinitiator. In this study, the transmission of blue light was likely reduced due to consumption of the photons by the camphorquinone. Unfortunately, the relative contribution of absorption by the photoinitiator to the overall reduction in light transmission in commercially available composites is small (21), and is mainly determined by the material composition and the wavelength of the incident light.

The average reduction in radiant flux in the violet region (7.37 and 8.47 times lower for VC and BPC, respectively) was more pronounced than in the blue region (3.09 and 4.64 times lower for VC and BPC, respectively). A similar result was obtained in the study by Harlow et al. (7). This is a well-known property of shorter wavelengths, which show stronger scattering compared to longer wavelengths described by the Rayleigh scattering equations (22). Based on the sufficiently known composition of the QuiXfil we can exclude the absorption of violet light by the alternative photoinitiators, hence the reduction of the radiant flux can be attributed to the scattering at the surface of the filler particles. Slight differences in the wavelengths of violet light of two polywave LCUs (409 nm for BPC and 401 nm for VC) did not result in a significant difference in violet light transmission. The scattering in the dental composites is highest when the size of the filler particles is half the wavelength of the incident light. This means that a filler size of 200-230 nm is unfavorable for light transmission, while larger or smaller sizes enable better light transmission. QuiXfil as a bulk fill composite has a higher translucency than conventional materials (23), which is most likely due to the large filler particle size of ~10 µm.

0,5%% za TW, 20,31 ± 0,79 % za BPC i 28,03 ± 3,14 % za VC od izvorne vrijednosti emisije svjetlosti odgovarajućih polimerizacijskih uređaja (slike 3., 4. i 5.). Vrijednosti ukupne transmisije svjetla bile su statistički različite za svaki FPU ($p < 0,001$). Transmisija plave svjetlosti također je bila najniža za jednovalni FPU TW, a slijede ga BPC i VC s najvišim vrijednostima ($p < 0,001$). Pri usporedbi dvaju viševalnih FPU-a, transmisija ljubičastog svjetla smanjena je za sloj debljine 2 mm na 12,02 ± 0,94 %, odnosno 13,81 ± 1,71 % za VC i BPC (slika 6.), bez statističke razlike među njima (p = 0,481 i p = 1,0 za BPC odnosno VC).

Rasprava

Cilj ove studije bio je istražiti utjecaj viševalnih FPU-a na transmisiju svjetlosti kroz kompozitni materijal koji sadrži kamforkinon kao jedini fotoinicijator i zato teoretski ne zahtijeva ljubičasti dio spektra za odgovarajuću polimerizaciju. Rezultati su pokazali da je transmisija svjetla poboljšana za viševalne FPU-e u usporedbi s kontrolnim jednovalnim FPU-om koji je imao najnižu ukupnu transmisiju svjetlosti (u rasponu 360 – 540 nm) i najnižu transmisiju plave svjetlosti (420 – 540 nm). Zato je nulta hipoteza odbačena. Možemo zaključiti da nema štetnog učinka viševalnih polimerizacijskih uređaja na transmisiju svjetlosti kroz sloj od 2 mm. Kao što se i očekivalo, transmisija svjetlosti niža je na ljubičastim valnim duljinama nego na plavima.

Smanjenje transmisije svjetlosti može se barem djelomično pripisati apsorpciji fotona fotoinicijatorima. U ovoj studiji je transmisija plave svjetlosti vjerojatno smanjena zbog potrošnje fotona kamforkinonom. Nažalost, relativni doprinos apsorpcije fotoinicijatora ukupnom smanjenju transmisije svjetlosti u komercijalno dostupnim kompozitima malen je (20) i uglavnom je određen sastavom materijala i valnom duljinom upadne svjetlosti.

Prosječno smanjenje toka zračenja u ljubičastom dijelu spektra (7,37, odnosno 8,47 puta niže za VC i BPC) bilo je izraženije nego u plavom dijelu spektra (3,09, odnosno 4,64 puta niže za VC i BPC). Sličan rezultat dobiven je u studiji Harlowa i suradnika (6). To je dobro poznato svojstvo kraćih valnih duljina koje pokazuju jače raspršenje u usporedbi s dužim valnim duljinama opisanima Rayleighovim jednadžbama raspršenja (21). Na temelju dovoljno poznatoga sastava QuiXfil-a možemo isključiti apsorpciju ljubičaste svjetlosti alternativnih fotoinicijatora, tako da se smanjenje toka zračenja može pripisati raspršenju na površini čestica punila. Male razlike u valnim duljinama ljubičastog svjetla dvaju viševalnih FPU-a (409 nm za BPC i 401 nm za VC) nisu rezultirale značajnom razlikom u transmisiji ljubičastog svjetla. Raspršenje u dentalnim kompozitima najveće je kada je veličina čestica punila upola manja od valne duljine upadne svjetlosti. To znači da je veličina punila od 200 do 230 nm nepovoljna za transmisiju svjetla, a veće ili manje veličine omogućuju bolju transmisiju svjetla. QuiXfil kao *bulk-fill* kompozit ima veću translucenciju od konvencionalnih materijala (22), najvjerojatnije zbog velike veličine čestica punila od ~10 µm.

Teorijom raspršenja ovisnog o valnoj duljini, prema kojoj se veće prigušenje postiže na kraćim valnim duljinama, a

The wavelength-dependent scattering theory, according to which higher attenuation is achieved at shorter wavelengths and lower attenuation at longer wavelengths, is used by Par et al. (21) to describe the fourfold higher light transmission of a polywave LED LCU compared to the monowave LCU, which differs by only 9 nm (21). The same explanation could be valid for the VC light transmittance values in the present study. The VC, the spectrum of which mostly extended towards longer wavelengths, achieved the highest light transmittance. The VC polywave LCU has four LED chips, two blue LEDs at 460 nm arranged diagonally to each other, one blue LED emitting at 440 nm, and one violet LED emitting at 400 nm (5). Therefore, the VC emission spectrum has three peaks, two of which are in the blue range, at 447 and 462 nm. The result is a very wide bandwidth of the VC emission spectrum, which most likely ensures the best light transmittance of this LCU in the current study. However, this explanation cannot account for the lowest light transmittance of the TW, monowave LCU, which has a peak emission at 453 nm, more than the BPC, which peaks at 449 nm in the blue region. If we look at the power as a function of time for TW, we can see that it increases in the first 3 seconds and then levels off to the maximum value. The optical curing time measured with the MARC was 0.5 s shorter than the 20 s selected with the LCU handpiece. Another possibility is that broad spectral coverage, such as in BPC and VC, was more favorable for blue and total light transmission than for the narrow-spectrum TW.

An increase in temperature during polymerization in the composite specimen can also improve light transmittance (24). The increase in temperature comes from the exothermic polymerization reaction, but some of the heat from the LCU is also transferred to the specimen (17). Third-generation LCUs with a high radiant exitance, such as those used in this study, can produce a significant heat radiation (5). Similarly, a high degree of conversion generates heat, but also changes the refractive index of the polymer network, thus resulting in various dynamic changes in the optical properties of the composite material, which can lead to an increase or decrease in light transmittance depending on the material composition (25).

This pilot study raises questions that require clarification of the results obtained. Follow-up studies on the influence of different curing units on the range of properties such as temperature rise and polymerization kinetics as a function of material depth and curing time are currently being carried out by the authors.

Conclusions

Within the limits of the current pilot study, we can conclude that the polywave LCUs can safely replace the monowave LCUs for the polymerization of composites activated exclusively with camphorquinone. Both tested polywave LCUs showed an improved light transmission compared to the monowave LCU used as control.

manje na duljim valnim duljinama, koriste se Par i suradnici (20) za opisivanje četverostruko većeg prijenosa svjetlosti viševalnog LED FPU-a u usporedbi s jednovalnim FPU-ima, koji se razlikuje za samo 9 nm (20). Isto objašnjenje moglo bi vrijediti za vrijednosti transmisije svjetla kod VC-a nađene u ovom istraživanju. Najveću transmisiju svjetlosti postigao je VC čiji je spektar uglavnom dosezao veće valne duljine. VC viševalni FPU ima četiri LED čipa, dvije plave LED diode na 460 nm raspoređene dijagonalno jedna prema drugoj, jednu plavu LED diodu koja emitira na 440 nm i jednu ljubičastu LED diodu na 400 nm (4). Stoga VC emisijski spektar ima tri vrha, od kojih su dva u plavom dijelu spektra na 447 i 462 nm. Rezultat je vrlo široki emisijski VC spektar, što najvjerojatnije osigurava najbolju transmisiju svjetlosti toga FPU-a u ovom istraživanju. Međutim, istim objašnjenjem ne može se protumačiti najniža transmisija TW svjetlosti, jednovalnoga FPU-a, koji ima vrh emisije na 453 nm, što je više nego BPC koji ima vrh vrijednosti na 449 nm u plavom dijelu spektra. Ako promatramo snagu kao funkciju vremena za TW, možemo vidjeti da ona raste u prve 3 sekunde, a zatim se ujednačuje do maksimalne vrijednosti. Vrijeme optičke polimerizacije izmjereno MARC-om bilo je za 0,5 sekunda kraće od 20 sekunda koje je odabrano vrijeme na kućištu polimerizacijskog uređaja. Druga je mogućnost da je široka spektralna pokrivenost, kao što je kod BPC-a i VC-a, bila povoljnija za plavu i potpunu transmisiju svjetlosti od uskoga TW spektra.

Povećanje temperature tijekom polimerizacije u kompozitnom uzorku također može poboljšati transmisiju svjetlosti (23). Povećanje temperature nastaje zbog egzotermne reakcije polimerizacije, ali se dio topline iz FPU-a također prenosi na uzorak (16). Treće generacije FPU-a s visokom emisijom zračenja, poput uređaja korištenih u ovom istraživanju, mogu proizvesti značajno toplinsko zračenje (4). Slično tomu, visok stupanj polimerizacije stvara toplinu, ali također mijenja indeks loma polimerne mreže te rezultira različitim dinamičkim promjenama u optičkim svojstvima kompozitnog materijala, što može povećati ili smanjiti transmisiju svjetlosti, ovisno o sastavu materijala (24).

Ovo pilot-istraživanje potaknulo je dodatna pitanja koja zahtijevaju objašnjenje dobivenih rezultata. Autori trenutačno provode daljnja istraživanja o utjecaju različitih polimerizacijskih uređaja na niz svojstava kao što su porast temperature i kinetika polimerizacije kao funkcija debljine materijala i vremena polimerizacije.

Zaključci

Unutar ograničenja ove pilot-studije možemo zaključiti da viševalni FPU-i mogu sigurno zamijeniti jednovalne FPU-e za polimerizaciju kompozita aktiviranih isključivo kamforkinonom. Oba testirana viševalna FPU-a pokazala su poboljšanu transmisiju svjetlosti u usporedbi s kontrolnim jednovalnim FPU-em.

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Sažetak

Cilj: Cilj ove studije bio je usporediti transmisiju svjetlosti jednovalnih i viševalnih fotopolimerizacijskih uređaja s pomoću *bulk-fill* kompozitnih materijala koji sadržavaju samo kamforkinon kao fotoinicijator. **Materijali i metode:** Tri fotopolimerizacijska uređaja korištena su za polimeriziranje *bulk-fill* kompozita QuiXfil: jedan jednovalni (Translux® Wave) i dva viševalna (VALO Cordless i Bluephase® PowerCure). NIST-kalibrirani spektrometar (MARC Resin Calibrator, BlueLight Analytics Inc.) rabljen je za mjerenje emitirane i propuštene svjetlosti kroz kompozitni uzorak od 2 mm tijekom 20 sekunda. Transmisija svjetlosti izračunata je iz omjera količine propuštene i emitirane svjetlosti. Za analizu podataka (ANOVA, $\alpha = 0,05$), odabrano je ukupno zračenje cijelog spektra, zračenje valnim duljinama od 360 do 420 nm za ljubičasti spektar i od 420 do 540 nm za plavi spektar. **Rezultati:** Jednovalni fotopolimerizacijski uređaj Translux® Wave imao je najmanju transmisiju svjetla (13,78 ± 0,5 %), slično prijenosu ljubičastog svjetla viševalnih uređaja (12,02 ± 0,94 % i 13,81 ± 1,72 % za Valo Cordless i Bluephase PowerCure, respektivno). Transmisija plavog svjetla (32,15 – 23,70 %) bila je više nego dvostruko veća nego za valne duljine u ljubičastom području spektra (13,81 – 12,02 %) za dva viševalna uređaja. VALO Cordless pokazao je najveću propusnost ukupnoga i plavoga svjetla ($p < 0,001$). Nije bilo značajne razlike u prijenosu ljubičastog dijela spektra između VALO Cordless i Bluephase® PowerCure ($p = 0,465$). **Zaključak:** Unutar ograničenja ove studije, možemo zaključiti da se viševalni uređaji za polimerizaciju mogu koristiti za polimerizaciju *bulk-fill* kompozita s kamforkinonom kao jedinim fotoinicijatorom.

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