PROFILE

Frederick Allen Rueggeberg (Fred), DDS, MS

Current Occupation
Full time academics

Education
BA University of Delaware, Newark, DE (June, 1974); DDS Emory University, Atlanta, GA (May, 1979); MS University of Michigan, Ann Arbor, MI (May, 1987)

Academic and Other Current Affiliations
The Medical College of Georgia (present)
Tenured, full professor
Section Director, Dental Materials

Most Notable Memberships in Professional Organizations
International/American Association for Dental Research
American Association of Dental Schools
American (and Georgia) Dental Association
Fellow, Academy of Dental Materials
American Dental Education Association

Most Notable Offices/Positions Held
Editorial/advisory board member for:
Journal of Esthetic and Restorative Dentistry
The Dental Advisor
Journal of Dental Research
Operative Dentistry
Journal of Prosthetic Dentistry
Inside Dentistry

Honors/Awards
Omicron Kappa Upsilon—Dental National Honor Society
Excellence in Teaching Award, School of Dentistry
Outstanding Faculty Award for School of Dentistry
Fellow, Academy of Dental Materials

Publications
(Five selected from 124 since 1987)
Bagis YH, Rueggeberg FA. Mass loss in Urethane/TEGDMA- and Bis-GMA-based resin composites during post-cure heating. Dent Mater 1997;13:377–80.
Daronch M, Rueggeberg FA, Goes MF. Polymerization kinetics of pre-heated composite. J Dent Res 2006;85:38–43.
Lazarchik DA, Hammond BD, Sikes CL, Looney SW, Rueggeberg FA. Hardness comparison of bulk filled/trans-tooth and incremental filled/occlusally irradiated composites. J Prosthet Dent 2007;98:129–40.
Brackett MG, Brackett WW, Browning WD, Rueggeberg FA. The effect of light curing source on the residual yellowing of resin composites. Oper Dent 2007;32:443–50.
Vandewalle KS, Roberts HW, Rueggeberg FA. Power distribution across the face of different light guides and its effect on composite surface microhardness. J Esthet Restor Dent 2008;20:108–17.

Notable Contributions to Dentistry
Extensively published in peer-reviewed Dental Journals (currently 124)
Extensive State, National, and International Lecturing (122 since 1992)
Hold 5 patents
"Method and Apparatus for Light-Curing Resin Adhesives for Orthodontic Brackets". US Patent issued September 1, 1998, #5,800,163.
"Fluorescent Agent for the Identification of Tooth Dentin—submitted April 24, 2000. May 21, 2002: US Patent # 6,391,281 issued.
"Fluoride-releasing amalgam dental restorative material". Issued August 27, 2002. US Patent # 6,440,398.
"Fluoride-releasing amalgam dental restorative material". Issued September 24, 2002. US Patent #6,455,609.
"Use of Integrating Sphere Technology to Provide Uniform, High-Intensity Light, and Wavelength Mixing from Light Emitting Diodes", provisional application number 60/756,862, filed January 7, 2006.

Hobbies or Personal Interests
Amateur radio
Electronics
Renovating houses
Solar/alternative energy sources

Any Other Items of Interest to Readers
1-year GPR at the Wilmington Medical Center, 1980
Associate in private practice (1980–1982)
Sole proprietor, general practice (1982–1985)
Married to the world's most AWESOME woman
Proud "Papa" of two of the MOST beautiful and MOST intelligent grand daughters in existence
Cannot spell or remember people's names
Favorite TV shows:
History Channel
Modern Marvels
Myth Busters
Seinfeld
Raymond

Masters of Esthetic Dentistry

Comparison of Manufacturer-Recommended Exposure Durations with Those Determined Using Biaxial Flexure Strength and Scraped Composite Thickness Among a Variety of Light-Curing Units

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ABSTRACT

Statement of the Problem: Manufacturer-recommended exposure durations for light-curing units are often understated and might not have true clinical relevance.

Purpose: To compare composite depths of cure among exposure durations provided by the manufacturer and those obtained when optimizing exposure duration for biaxial flexural strength or for composite compule-scraping tests when using different light-curing units.

Methods/Materials: A hybrid composite (Prodigy, A3, Kerr, Orange, CA, USA) was exposed to different light-curing units (all manufactured by Kerr Demetron) (conventional quartz-tungsten-halogen [QTH], conventional blue light-emitting diode [LED_{CONV}] or a high-intensity blue LED light [LED_{HIGH}]) for various amounts of time, including that recommended by the manufacturer for the

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given light. A test model was designed in which 0.5-mm thick composite discs were stacked between Mylar sheets to a total composite thickness of 3.0 mm. The top of each stack was exposed to the different lights for a variety of exposures at a 2-mm distance. Twenty-four hours later, the stacks were disassembled, and the individual discs from each 0.5-mm thick increment were tested for biaxial flexure strength. Ten discs were made for each exposure duration from each light. Statistical analysis (analysis of variance, Dunnett–Hsu post hoc test, $\alpha = 0.05$) was used to identify the exposure duration needed for the flexural strength at a 2.5-mm depth (manufacturer-recommended thickness) to be similar to that at the topmost 0.5-mm thick increment. Compules of the same composite were modified to form cylinders in which their contents were forced to one end and photopolymerized (at a 2-mm distance) for a variety of exposure durations using the same light units mentioned above ($N = 5$). Twenty-four hours later, compule contents were extruded, and the unpolymerized residue was removed using hand scraping with a plastic spatula. The thickness of the resulting specimen was measured, and was plotted as a function of exposure duration for each light. Regression analysis was applied to generate the mathematical correlation between exposure duration and resulting composite scraped thickness. Manual line-drawing methods were used on that generated plot to determine the major inflection in the exposure–thickness relationship that changed, and the exposure time correlated to that inflection point was considered the optimal exposure duration from this method.

Results: Manufacturer-recommended exposures for a 2.5-mm thick composite increment from the lights used were: QTH 20 seconds; LED_{CONV} 10 seconds; and LED_{HIGH} 5 seconds. Flexural strength and scraped composite compule thickness values markedly changed with increase in exposure duration and differed among the lights. Exposure durations needed to provide similar flexural strength at 2.5 mm as that of the topmost increment were: QTH 30 seconds; LED_{CONV} 15 seconds; and LED_{HIGH} 20 seconds. Exposure durations derived from inflection points of the scraping plots provided optimal exposure duration values of: QTH 25 seconds; LED_{CONV} 15 seconds; and LED_{HIGH} 17 seconds.

Conclusions: In all cases, use of manufacturer-recommended exposure duration provided a lower flexural strength or scraped composite thickness than did longer exposures used. Exposure durations using the simple scraping method correlated very well with those of the much more sophisticated biaxial test.

CLINICAL SIGNIFICANCE

No one can provide a clinician with the optimal exposure duration to use for a given light and a specific lot, shade, and brand of composite. Instead, manufacturers offer a single exposure that is meant to be used for all clinical scenarios and operating conditions. The results of this test indicate that manufacturer-recommended exposures proved inadequate to optimize the flexural strength of the recommended increment of composite, but longer exposures were required. The exposure durations determined from the much more simplified composite compule-scrape test proved to match those found to optimize biaxial flexure testing for each light used. Clinicians can thus adapt this very simple in-office scraping test to develop their own customized exposure guide, providing them with exact exposure durations that will

optimize composite properties, thus eliminating the guesswork from this most important aspect of chairside dentistry.

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INTRODUCTION

Clinicians are keenly aware of the importance of providing an appropriate exposure duration from light-curing units. Over the past 10 years, manufacturers have introduced light-curing units of various types and ever-increasing power: quartz-tungsten-halogen (QTH); high power QTH, argon-ion laser; plasma arc (PAC); light-emitting diode (LED); and high-intensity LED units. Along with the introduction of increasingly powerful lights, the manufacturer-recommended exposure durations have decreased from 40 or 60 seconds to as little as 5 seconds (or less). Clinicians rely on these recommended values to generate optimal results when placing photoactivated restorative materials. However, very little information is provided about what a stated exposure time is supposed to accomplish; the clinician is merely supplied with a time to use. No adjustments are provided to compensate for the effect of composite type or shade, the characteristics of the light-curing unit used (power density, spectral distribution), or the distance between the light tip and the target restorative material. Because these factors have unknown effects on the resulting restoration quality, clinicians often will double the recommended exposure time, just to be "on the safe side." Conversely, some might halve the recommended time, thinking manufacturers have "padded" the time, just to be on the "safe side."

In a busy practice, exposure duration can have an impact on the total time of a procedure, and many clinicians are concerned with the effect of time spent photo curing on the profitability of some treatments. The clinician is placed in a situation of trying to provide optimal dentistry but in minimal time. With exposure durations of 5 seconds being advocated by some curing light manufacturers, clinicians are automatically drawn to such times in hopes of realizing a significant reduction in time spent with a patient—but at what true cost?

The topmost surface of a composite is readily polymerized in a very short time, even using low power density from relatively remote distances, as little light is lost.[1] Hardness of this outer surface is typically the only parameter a clinician has for identifying the adequacy of curing light use. However, the loss of light intensity with increasing depth in a composite is very high, resulting in the deeper layers not polymerizing as well as the top, exposed surface.[1–3] This change in polymerization (monomer conversion) with depth from the top, irradiated surface has been termed the "depth of cure."[2]

Properties of the photoactivated restorative material are affected by the extent to which it polymerizes.[4–12] The extent of energy available to provide the "work" of polymerization will directly influence the extent of composite cure.[13] The total energy provided is calculated by multiplying the power density of the light by its exposure duration.[14] Each type of photo-curable restorative material requires a different amount of energy for optimal polymerization.[15] Reducing either of these two parameters will require a concomitant increase in the other to ensure that the proper amount of photo-curing energy is provided.[16] Because a great amount of light is available at the top, exposed composite surface, the exposure time needed to generate a well-polymerized surface is quite short. However, light is reduced at

a remarkable rate as it penetrates the composite,[1–3] meaning that longer exposure durations are required to provide local composite properties that are similar to those of the top, irradiated surface.

One goal in light-activating a composite would be to provide a thickness of material having uniform properties throughout the increment being generated. With the development of a uniform, thick layer of rigid composite, flexure of the material under stress becomes greatly reduced. High levels of composite cure increase its bulk flexural properties,[5,10] reducing the potential for fracture. In addition, with less flexure, lower fatigue stress is developed at the tooth-restoration interface,[17] potentially increasing the duration of an effective bond. Therefore, it would behoove the clinician to provide maximal, uniform conversion of each composite increment placed.

Many factors affect light penetration through a composite, and thus the extent of the localized polymerization reaction. Composite filler composition, size, and amount affect the level of light available to stimulate the photoinitiator.[2,18,19] Different amounts of shading pigments are added to provide similarity of color between the restoration and surrounding tooth structure. However, these pigments can reduce light penetration, and thus polymerization.[20] The resin matrix itself can absorb light, but as the composite polymerizes, its ability to transmit light actually increases because the refractive index of the polymer becomes closer to that of the filler.[21]

Recently, alternative photoinitiating systems have been introduced into some restorative materials. Besides the commonly used camphorquinone initiating system, other photoinitiators that are more efficient and less chromatic are used where high degrees of translucency or value are required.[22,23] The alternative photoinitiators require wavelengths shorter (approaching the violet spectral region) than those required for camphorquinone. With increasing composite depth, shorter wavelength light is preferentially filtered over that of blue light, meaning that the spectrum of photoactivating photons is not reduced uniformly with depth.[24] Specifically, light in the violet spectral region is more rapidly reduced than blue light, and thus the effectiveness of these initiators at composite depths might be seriously affected.[23]

Factors related to the light emitted from the curing unit toward the composite have a significant impact on composite cure and its resulting properties as well. The spectral distribution of light falling on the composite must meet the needs of the photoinitiator.[25] When such a correlation exists, optimal photo curing can occur. However, the emission spectra of light-curing units varies greatly, as does the power delivered at different wavelengths.[26] Of specific import currently is the distribution of spectral emission from LED units. The effective wavelength span of an LED is much less than that of a filtered QTH or PAC light, meaning that not all possible activation states of the photoinitiator are accessed.[27] Some blue LED lights will not polymerize specific restorative materials.[28] As a result, some manufacturers are now providing LED lights with multiple frequency chips to provide a much broader spectral distribution of emitted light.[29] However, knowledge of which specific composites require what spectral light distribution for optimal photopolymerization is left to the practitioner to determine.

The distance of the distal, light-emitting end of a light-curing unit to its intended target is also influential in determining the power delivered to the restoration, and thus the potential for generating the polymerization process.[1–3] However, the recommended exposure times provided by light-curing units or composite manufacturers do not take this important aspect into consideration.

Again, it is left to the clinician to determine what is optimized at a manufacturer-recommended exposure duration and to what incremental thickness the recommendation is valid. Can one exposure value adequately accommodate for differences among light-curing units (power emitted and spectral distribution), differences in composite composition and photochemistry, or changes in tip-to-composite distances? With the success of a clinician being based, at least partly, on the durability of his or her restorations, the exposure duration used is essential for providing optimal restoration properties but should involve minimal chairside time. Perhaps the only way clinicians can be assured that they are using an optimal exposure duration is to directly measure the performance of their light-curing unit with their specific restorative materials, as no manufacturer or research study can really supply such information.

The purpose of this study was to investigate the adequacy of manufacturer-recommended composite exposure durations from different types of light-curing units on a variety of material properties. Results using recommended exposure durations were compared with those found to optimize composite properties using a composite scraping test and to a more complicated laboratory test: the biaxial flexural strength test. Correlation of optimal exposure durations between biaxial testing and the simple composite compule-scraping method was examined to gauge the adequacy of the easily performed scraping test to reflect similar changes in this clinically important physical property.

MATERIALS AND METHODS

The light-curing units and composite used are listed in Table 1. For consistency, the same lot of composite was used for all test procedures. The light-curing units

TABLE 1. COMPOSITE AND LIGHT-CURING UNITS USED.

Composite Brand name	Shade	Lot number	Manufacturer	Location
Premise	A3 Body	2743773	Kerr Corporation	Orange, CA, USA

Light units Brand name	Serial number	Classification	Code used in manuscript	Exposure duration (second) for specific composite used* (2.5-mm increment)	Exposure durations for biaxial tests (second)	Exposure durations for scraping tests (second)
Optilux 501	58120742	Quartz-tungsten-halogen	QTH	20	10, 20, 30, 40, 60	10, 20, 30, 40, 50, 60
LE Demetron 1	70003844	Conventional, second-generation blue LED	LED_{CONV}	10	5, 10, 15, 20	5, 10, 15, 20, 40, 60
DEMI	P4	High-intensity, second-generation blue LED	LED_{HIGH}	5	5, 10, 15, 20	5, 10, 15, 20, 40, 60

*Supplied by the manufacturer.
DEMI = output from the LED_{HIGH}; LED = light-emitting diode.

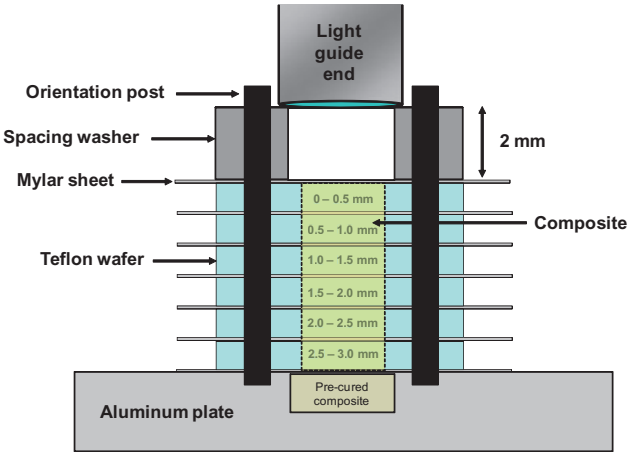

Figure 1. Correlation of an intact composite cylinder with a "theoretical" cylinder consisting of stacked 0.5-mm-thick segments as used in the current study.

selected represented a wide variety of devices commonly in use: a conventional QTH, a conventional, second-generation blue LED unit (LED_{CONV}), and a high-intensity blue LED (LED_{HIGH}).

Curing Light

Irradiance Measurement

The light-emitting end of each curing unit was directed into a 6" integrating sphere (CSTM-LMS-060-SF, Labsphere, North Sutton, NH, USA). Radiant power falling on a small portion of the inner wall of the sphere was directed to a diode-array spectral radiometer (USB2000, Ocean Optics, Dunedin, FL, USA) using a fiber optic patch cord. The output of the spectrometer was fed to a personal computer where software (SpectraSuite, Ocean Optics) calculated absolute radiance values and displayed them on the screen. The spectral power values were placed into a spreadsheet program (Excel 2003, Microsoft Corporation, Redmond, WA, USA), where the total radiant power between 350 and 550 nm was determined. The system was calibrated using a NIST-traceable light source (CAL-IHLS-100-35, Labsphere). Five replications were made for each test condition. Prior to all readings of the QTH light, the unit was activated for 60 seconds in order to obtain stable output values. Power values for the LED_{HIGH} unit were recorded for both the baseline and high, pulsed levels. The diameter of the fiber-optic bundle of each light guide was measured. Output power values were divided by the tip fiber optic area to obtain values of irradiance (power density; mW/cm^2).

Flexural Modulus Testing

The purpose of this test parameter was to fabricate simulated cylinders of composite from which 0.5-mm-thick wafers could be extracted at known depths from the top, irradiated surface, and then tested for biaxial flexural strength (Figure 1). To accomplish this goal, 0.5-mm-thick squares of virgin Teflon were custom fabricated (Cannon Gasket, Inc., Upland, CA, USA) such that they had a central, circular opening (6.5 mm diameter), and two smaller openings (3.5 mm diameter) each centered 10.0 mm lateral to the larger central hole. A custom test jig was fabricated consisting of a flat, lower aluminum plate, into which a 5-mm deep, 8-mm-diameter recess was made. The line angle at the junction of the vertical walls and the recess floor was slightly undercut to provide mechanical retention. This recess was incrementally filled with composite and was light-cured. The block and composite were finished flat. Two holes were made on either side of the composite, spaced similarly to the small holes in the Teflon wafers. Steel rods (8-mm long) were pressed into these holes, extending vertically, perpendicular to the composite-filled flat surface. This assembly was referred to as the "holding fixture."

Two holes (5 mm in diameter) were punched into a small sheet of

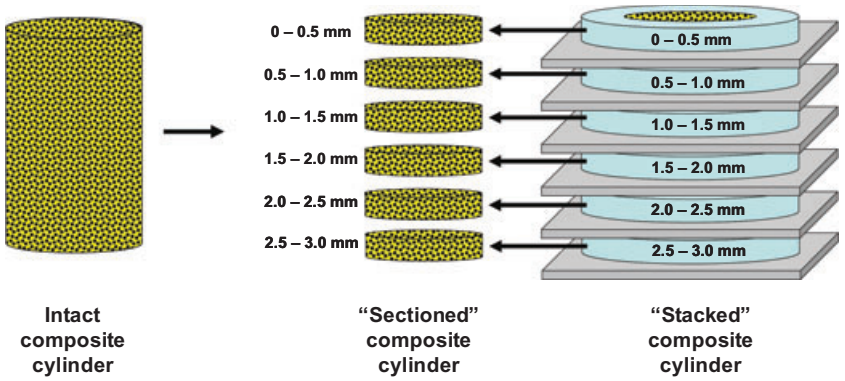

Figure 2. Diagram of test setup used to fabricate a "stack" of 0.5-mm-thick composite discs to simulate an intact composite cylinder.

Mylar (type D, 0.09-mm thick; DuPont, Wilmington, DE, USA), spaced at a similar distance as the inter-post dimension of the holding fixture. A small amount of optical immersion oil (type B, R. P. Cargille Labs Inc., Cedar Grove, NJ, USA) was placed over the cured composite surface, and a prepared Mylar sheet was lowered into place, using the vertical bars as guides. The oil acted to eliminate any air interface between the Mylar and the composite surface, increasing light transmission into and reflection from the underlying cured composite.

Next, a Teflon wafer was placed, using the two guide holes to lower it in a controlled manner onto the Mylar sheet covering the cured composite surface. Pilot testing determined the amount of composite paste to place into the central disc-shaped opening of the Teflon wafer. The amount added resulted in minimal excess when pressed and also totally filled the shape confines. The composite paste was placed, another Mylar sheet was lowered over it, and a flat aluminum pressing plate (also having holes matching the vertical posts of the holding fixture) was lowered over all added components. The assembly was taken to a press where 5 kg of force was applied for 1 minute to cause composite flow and adaptation to the confines of the disc-shaped hole.

Following this treatment, the pressing plate was removed and another Teflon wafer was lowered through the guide posts, composite paste placed, a Mylar sheet added, the pressing plate positioned, and the load applied. This process was continued until a total of six Teflon wafers were filled with composite; at 0.5-mm thick each, a total composite thickness of 3.0 mm was achieved. An additional Mylar sheet was placed on the topmost composite-filled Teflon wafer prior to pressing. Once all six wafers were in place, a 2-mm-thick metal washer, with a central 10-mm diameter hole, was placed over the assembly, again using holes made to fit the dimensions of the two vertical positioning posts. The assembly was placed on top of a laboratory jack stand, and was raised so that the upper surface of the washer was at the same level as the distal end of the light curing guide: 2 mm from the top Mylar surface (Figure 2). The light-curing unit was activated for the prescribed time (Table 1), the jack stand lowered, and the "stack" of composite discs was lifted vertically in one piece so that it was free from the orientation posts. The assembly was stored at room temperature in the dark for a period of 24 hours.

After this storage period, the stack components were separated, and the individual polymerized composite discs were retrieved and marked as to the surface facing the light-curing unit, and they were then individually placed into a testing jig. The jig consisted of a suspending ring, on which the composite specimen was concentrically placed. A movable, vertical shaft was in a fixed, concentric position with relationship to the center of the specimen. The end of the shaft contacting the upper

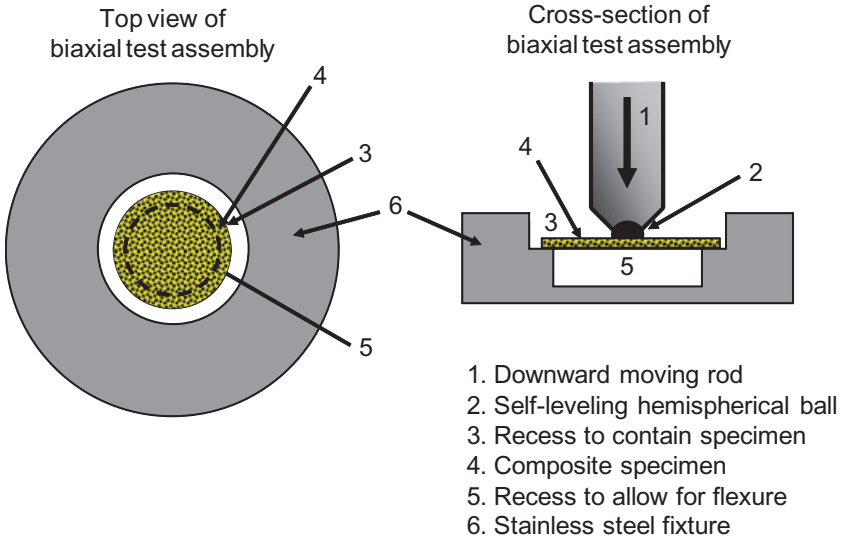

Figure 3. Schematic diagram of test jig used for biaxial flexure strength.

composite specimen surface had a concave recess into which a steel half bearing (1.58-mm diameter) was placed and held in position with lubricant paste. The configuration allowed the half bearing to pivot so that its total sectioned area always contacted the composite surface normal to its surface (Figure 3). The test jig was placed in a universal testing machine (model 5844; Instron Corporation, Canton, MA, USA), and a downward load was applied at the rate of 0.5 mm/min. The applied load was continuously monitored, and the value recorded at specimen fracture was noted. This value and the specimen dimensions were entered into software, where the biaxial flexural strength was calculated using the following formula:[30]

$$S = -0.238 * 7P(X - Y)/d^2 \quad (1)$$

where S = maximum center tensile stress (MPa) and P = total load (N) causing fracture

$$X = (1+\nu)\ln\left(r_2/r_3\right)^2 + \left[(1-\nu)/2\right]\left(r_2/r_3\right)^2 \quad (2)$$

$$Y = (1+\nu)\left[1+\ln\left(r_1/r_3\right)^2\right] + (1-\nu)\left(r_1/r_3\right)^2 \quad (3)$$

in which υ = Poisson's ratio (value); r_1 = radius of support circle (mm); r_2 = radius of loaded area (mm); r_3 = radius of specimen (mm); and d = specimen thickness (mm) at fracture origin.

For a given light-curing unit used, the order of stack fabrication with respect to exposure duration was randomized in order to reduce the effects of operator learning on data variation. Ten stacks were made for each exposure duration and light-curing unit used. For each light, the data at each depth and each exposure duration were tested for normality using the Shapiro–Wilk test. If the assumption of normality was accepted for all depths at each duration, the Dunnett–Hsu method of performing all pairwise comparisons with a control in a repeated measures design was used to compare the flexural strength at each depth with that at the "control" depth of 0.0 to 0.5 mm. This analysis was performed separately for each exposure duration, using a family-wise error rate of 0.05 at each duration. If the normality assumption was not accepted for all combinations of depth and duration, then the Dunnett–Hsu method based on ranks was used to carry out the comparisons with the "control" depth.[31] The entire statistical analysis was performed using SAS 9.1 for Windows (2003; SAS Institute Inc., Cary, NC, USA).

Monomer Conversion of Tested Disc Surfaces

Following specimen fracture, a large fragment of each specimen was retrieved and used to obtain the infrared spectrum of the top and bottom surfaces, from which the degree of monomer conversion was determined. For this test, one

side of the specimen was positioned over the diamond element in a horizontal attenuated total reflectance unit (model 10500, Golden Gate Mk II; Specac Inc., Cranston, RI, USA). The specimen was adapted against the diamond surface using the attachment press. The unit was positioned in the optical bench of a Fourier transform infrared spectrometer (FTS-40; Bio-Rad, Digi-Lab, Cambridge, MA, USA), and the infrared spectrum was obtained using 16 scans at 2 cm^{-1} resolution. Following testing, the same specimen was turned over, and the spectrum of the opposite disc side was obtained in similar manner. The degree of monomer conversion (extent of utilization of available methacrylate C=C units during the polymerization process) was determined using methods previously described in the literature.[32–34] Basically, these methods utilize changes in the ratio of absorbance peaks of the aliphatic C=C (1,636 cm^{-1}) to the aromatic C=C (1,608 cm^{-1}) functional groups in the polymerized and unpolymerized states. The infrared spectrum of uncured paste was obtained by placing a small piece of the material directly on the diamond element.

Statistical analysis consisted of a series of one-tailed, unpaired *t*-tests made between the bottom surface of one composite stack increment and the top surface of the succeeding composite increment. The concept being tested was to evaluate how well the test setup replicated formation of an "intact" cylinder, where, conceptually, there would be no difference in conversion between these sites. The preset alpha was 0.05.

Composite Scraping Depths of Cure

Compules of the same composite lot used for flexural strength were modified to use as plastic cylinders in which uncured composite paste was held. To accomplish this task, the compule plunger was removed, and the curved compule spout was sectioned from the main cylindrical compule body. This process left the bolus of uncured composite paste retained within the plastic cylinder. A Mylar strip was placed on the table top, and the end of the compule previously retaining the plunger was placed on top of that sheet, and the flat end of a dental hand instrument was used to compact the composite paste against the Mylar. The compule was then placed in an acrylic jig, holding the prepared compule vertically, with its Mylar, composite-filled end facing up. The acrylic jig was placed on the platform of a laboratory jack stand and was raised vertically until it was 2 mm from the distal end of the light-curing guide, both of which were concentric. The light-curing unit was activated for one of a variety of exposure durations (Table 1). The exposed compule was removed from the jig and placed in a Manila envelope that was stored in the dark at room temperature for 24 hours.

Following this time, the compule was placed into a hand gun dispenser (compule dispensing syringe; Centrix Inc., Shelton, CT, USA), and the composite contents were ejected. A plastic spatula was used with manual pressure to remove the residual, uncured composite paste. Thickness of the remaining, hard composite specimen was measured with a digital micrometer (model 331-711-10; Mitutoyo America Company, Aurora, IL, USA) to a precision of 0.001 mm.

Five replications were made for each exposure duration and light-curing unit. A spreadsheet program (Excel 2003) was used to plot the thickness of polymerized composite as a function of exposure duration for each light-curing unit. The software was also used to provide a nonlinear regression fit of the data to a natural logarithmic regression line. Using this regression plot, lines were drawn: one tangent from the initial plot region; and another tangent to the end portion of the line (Figure 4). The intersection of these lines was considered as coincident with the inflection point of the curve, similar to that of the peak in the first derivative.

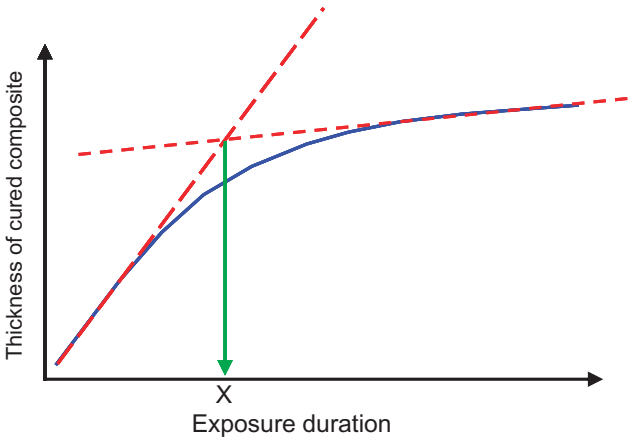

Figure 4. Schematic depicting determination of inflection point in curvilinear data (blue line = simulated test data; green line = drawn from intersection of dotted lines to x-axis to determine x-axis value of the inflection point; long-dashed red line = segment drawn tangent to initial portion of test data; short-dashed red line = segment drawn tangent to last portion of test data).

The exposure time represented by the intersection of these points was considered that value of time after which additional exposure resulted in a lower rate of increase in scraped thickness of composite. In other words, this time was considered as the optimal exposure duration, after which a diminishing return in composite thickness was seen for a given additional increment of exposure time. This analytical method is similar to that used in thermal analysis to determine onset of heat capacity changes as a function of temperature from differential thermal analysis data.[35]

Correlation of Exposure Times for Optimal Composite Performance

The manufacturer-recommended exposure durations for this specific composite and shade were provided at a depth of 2.5 mm (detail sheet included with product). These stated exposure times were compared to those times at which the flexural strength at 2.5-mm deep was first seen to be not different from that at the top 0.5-mm-thick increment. In addition, the optimal exposure value determined using the compule-scraping method was compared with the other two values to see how well the scraping test matched the recommended value as well as that at which flexural strength was optimized at that depth.

RESULTS

Light Unit Irradiance

Power density of the QTH light measured 602 (±2) mW/cm^2 between 370 nm and 510 nm (Figure 5). The LED_{CONV} unit (LE Demetron 1) had a power density of 593 (±1) mW/cm^2, with a peak output occurring at 460 nm, beginning at 430 nm and ending at 495 nm. The output from the LED_{HIGH} (DEMI) unit had a periodic, higher-level value and a longer, baseline value. During the high output segment (lasting 0.3 seconds), power density measured 1,434 (±5) mW/cm^2, and during the baseline portion (lasting 0.7 seconds), the output dropped to 1,183 (±2) mW/cm^2. The peak output for both output values occurred at 454 nm, with radiation starting at 420 nm and ending at 500 nm.

Monomer Conversion

The overall average difference in monomer conversion between the bottom of one composite increment and the top of the next among all the test specimens was 1.1 ± 0.9%, with the maximum being 3.6%. For the individual light-curing units (pooling all exposure duration values), the average difference for the QTH light was 1.4 ± 1.0% with a maximum of 3.6%, for the LED_{CONV} light 1.3 ± 0.8%, maximum of 2.8%, and for the LED_{HIGH} 0.7 ± 0.9%, with a maximum difference of 3.0%. Among all the paired comparisons (total of 70), 22 (31%) had a significant difference in conversion values. However, as seen earlier, these differences, although

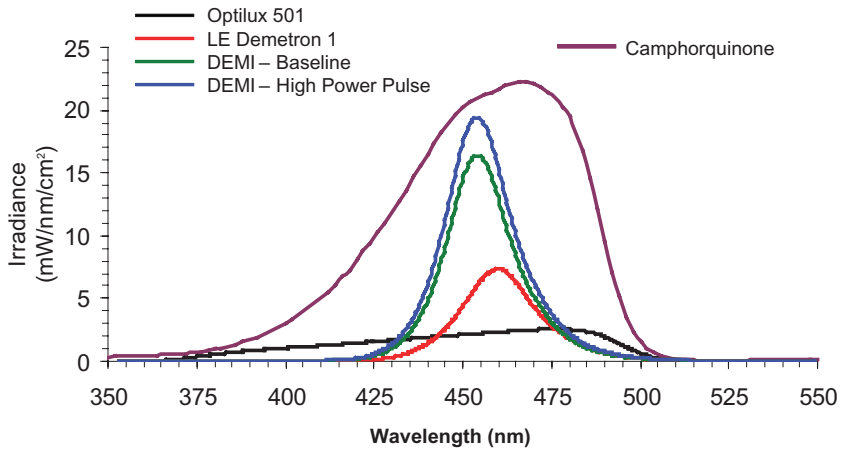

Figure 5. Spectral irradiance of the light-curing units used with the spectral absorption profile of camphorquinone superimposed (absorbance values have been adjusted to provide similar-scale readings as irradiance values).

significantly different, are quite small in absolute value.

Flexural Strength

The relationship between exposure duration and flexural strength of subsurface composite increments for the different light-curing units is shown in Figure 6. For all lights, as exposure duration was increased, the flexural strength at incremental layers deep to the top, irradiated increment became higher. For each light exposure, the deepest composite increment that still provided a flexural strength similar to that of the topmost, 0.5-mm-thick increment was considered the "flexural strength depth-of-cure" (FSDOC).

The flexural strength data for the QTH light (Figure 6A) were not normally distributed for all combinations of depth and exposure duration. Therefore, the rank-based Dunnett–Hsu method was used to compare each depth with the control depth of 0.0 to 0.5 mm separately for each exposure duration. The relationship between exposure duration for the QTH light and FSDOC was as follows (Figure 6A). For the 10 seconds exposure, similar flexural strength as that of the top 0.5-mm-thick surface was seen to a depth of 1.5 mm (10 seconds/1.5 mm). The remaining exposures and their FSDOC values were as follows: 20 seconds/2.0 mm; 30 seconds, 40 seconds, and 60 seconds/ 2.5 mm.

The flexural strength for the LED_{CONV} light (Figure 6B) also were not normally distributed for all combinations of depth and exposure duration. Again, the rank-based Dunnett–Hsu method was used to compare each depth with the control depth of 0.0 to 0.5 mm separately for each exposure duration. For the conventional LED light (Figure 6B), exposure duration and FSDOC were 5 seconds/ 1.5 mm, 10 seconds/2.0 mm, and 15 and 20 seconds/2.5 mm.

The flexural strength data for the LED_{HIGH} light were normally distributed for all combinations of depth and exposure duration. Therefore, the Dunnett–Hsu method was used to compare each depth with the control depth of 0.0 to 0.5 mm separately for each exposure duration. Using this light (Figure 6C), FSDOC results were 5 seconds/0.5 mm, 10 seconds/ 1.5 mm, 15 secomds/2.0 mm, and 20 seconds/2.5 mm. For all of the light-curing units tested, at the 3.0-mm depth, no exposure duration used provided a flexural strength that was statistically similar to that of the topmost increment.

Flexural strength values of composite at the 2.5-mm depth using exposure durations for each light that provided statistically similar strength values as the respective top, irradiated surfaces are seen in Figure 7. The LED_{CONV} (15 and 20 seconds), LED_{HIGH} (20 seconds), and QTH (30 and 40 seconds) all produced similar flexural strength values at this composite depth. However, the flexural strength

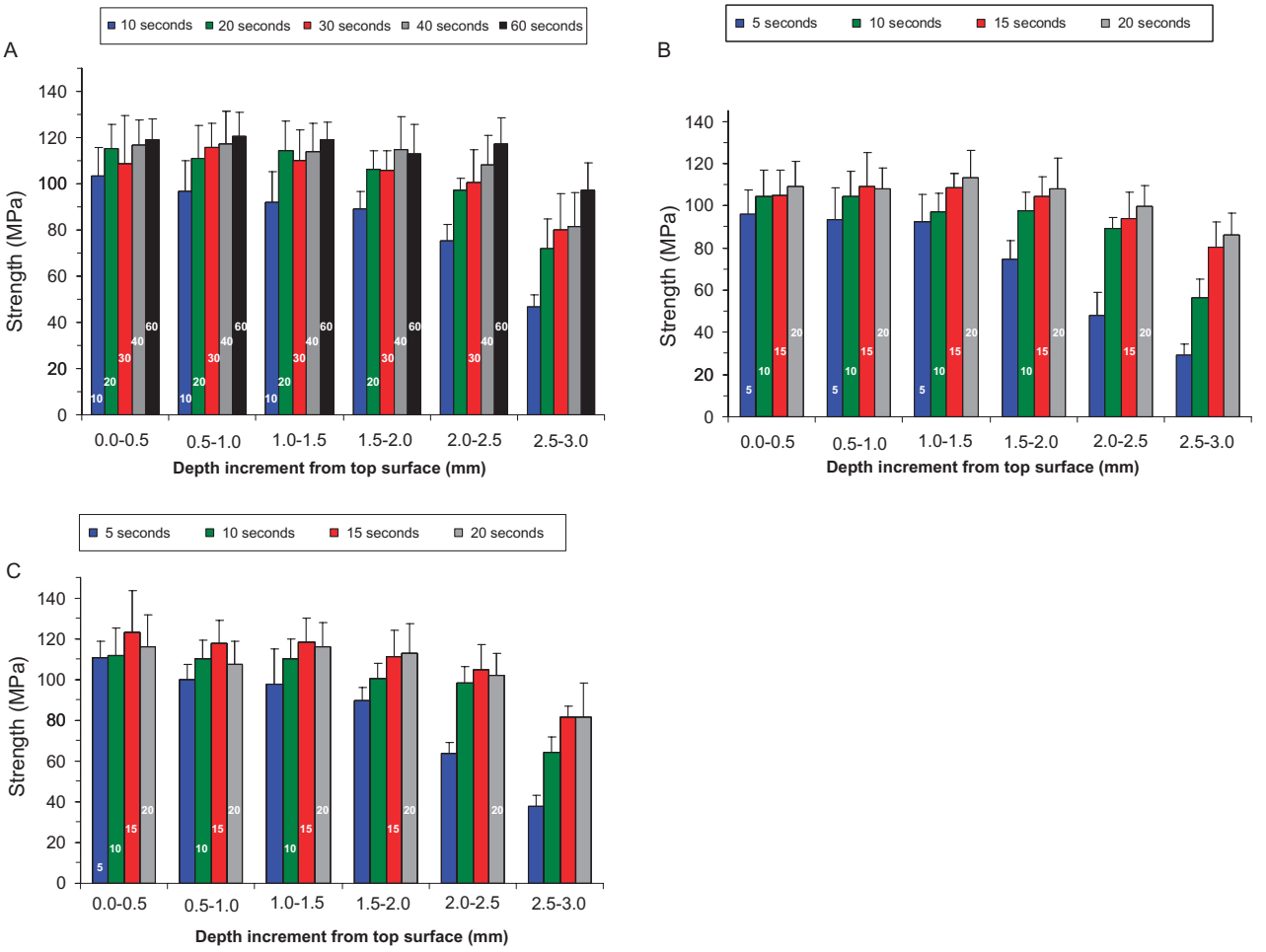

Figure 6. Biaxial flexural strength values obtained at different exposure durations among light-curing units: (A) quartz-tungsten-halogen, (B) conventional blue light-emitting diode (LED), and (C) high-intensity blue LED light. For a given light and within a specific exposure duration, bars having similar white numbers have flexural strength values that are not significantly different from the top, irradiated 0.5-mm-thick increment (N = 10 specimens per experimental group; vertical bar = + 1 SD).

resulting from the QTH (60 seconds) was not different from that of the 40 seconds QTH or 20 seconds LED_{HIGH} but was significantly greater ($p < 0.05$) than all the LED_{CONV} values (15 and 20 seconds) as well as that of the 30 seconds QTH exposure.

Compule Scraping

Figure 8 presents the results of the effect of exposure duration on scraped composite thickness for all lights tested. In each instance, regression analysis using a natural log resulted in an excellent fit of the data to the projected equation: QTH $R^2 = 0.9976$, LED_{CONV} $R^2 = 0.9735$, and LED_{HIGH} $R^2 = 0.9895$. Thus, the equation plots were used to draw the tangent lines needed for determining the inflection points correlating to optimal "performance" of composite with respect to exposure

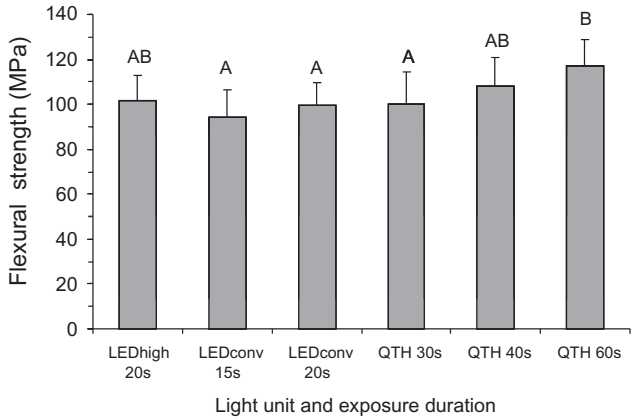

*Figure 7. Flexural strength values of composite derived when exposure duration provided value at 2.5-mm depth that was not different from that at the top 0.5-mm increment (*N = *10 specimens per group; vertical bar = +1 SD). Groups depicted by similar upper case letters are not statistically different.*

duration. For the QTH light, the inflection occurred at a projected exposure time of 25 seconds (Figure 8A), for the LED_{CONV} light, the inflection occurred at 15 seconds (Figure 8B), and using the LED_{HIGH} unit, the inflection occurred at 17 seconds (Figure 8C).

Correlation of Optimal Exposure Durations: Biaxial Flexure Strength and Scraping Thickness

Figure 9 displays the manufacturer-recommended exposure duration for each light-curing unit for a 2.5-mm-thick composite increment. Also shown in this figure are the exposure durations providing similar biaxial flexural strength at 2.5 mm as that seen at the top, irradiated surface (FSDOC) as well as the exposure duration values determined by inflection points in the correlation of exposure duration and scraping thickness graphs.

For the QTH light, the recommended exposure time of 20 seconds was lower than that found using the scraping method (25 seconds), which was less than that found using flexural strength (30 seconds or more). The recommended time for the conventional LED light was 10 seconds, but scraping and flexural testing indicated that 15 seconds was more appropriate. When using the high-intensity LED unit, the manufacturer recommended an exposure duration of 5 seconds. However, scraping (17 seconds) and flexural strength (20 seconds) indicated longer exposures would be more appropriate.

DISCUSSION

Validation of the Test Model

Although significant differences in conversion values were found between the bottom surface of one composite disc increment and the top surface of the underlying specimen in about 30% of the instances, the absolute values of these differences were very small, with the maximum being 3.6%, but most others averaging near only 1%. With this small difference noted, it can be assumed that the experimental model developed (i.e., generating composite "slices" by interposing Mylar sheets between 0.5-mm-thick composite increments) met the objective of fabricating a theoretical cylinder of composite that was photo-cured on the top surface, from which discs of cured material could be retrieved at known depths below the irradiated surface (Figure 1). The advantage of this test setup was that no sectioning was required. Sectioning of an intact composite cylinder would have interposed many variables. First, the thickness of the blade used to cut the specimen would permanently remove material needed for evaluation and would have disrupted the precise control of obtaining composite from specific depths. In addition, the lubricant action of irrigating fluid required for sectioning would have leached residual, unreacted monomer, perhaps greatly changing the

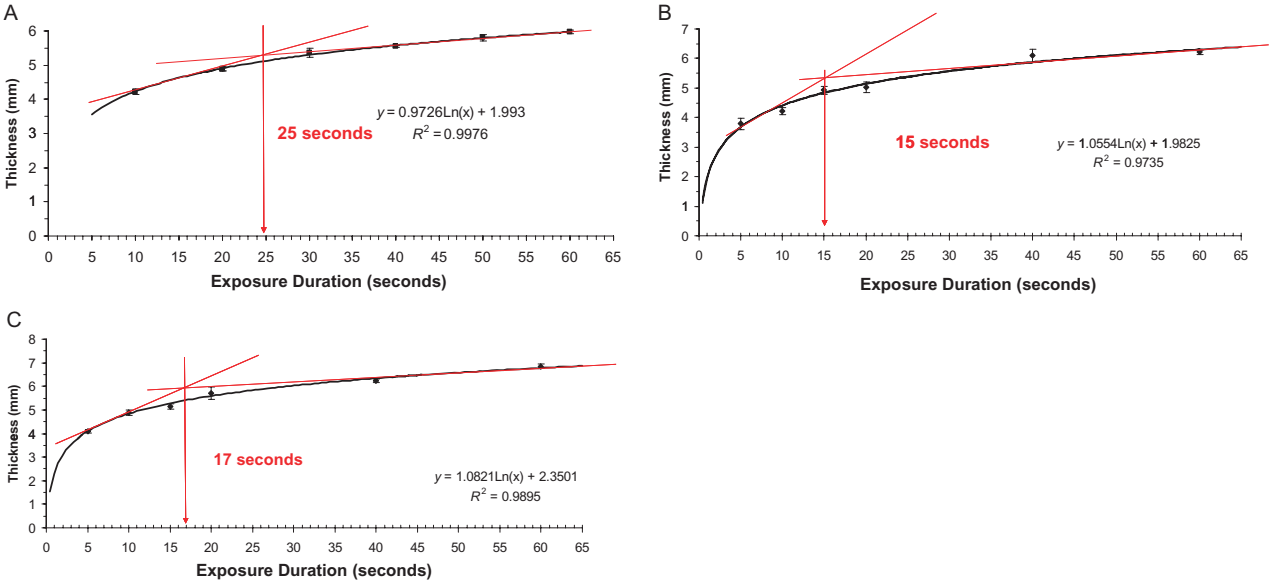

Figure 8. Scraping thickness of composites exposed using various time durations from different light-curing units: (A) quartz-tungsten-halogen, (B) conventional blue light-emitting diode (LED), and (C) high-intensity blue LED light. Inflection point determined by tangent line method and inflection time correlated to that point is presented in the figure.

physical properties of the resultant specimen, rendering it not truly representative of material polymerized under the local conditions imposed.[36]

Flexural Strength—Experimental Model

This testing is not the first to demonstrate differences in composite flexural strength related to differences in photo curing. Various authors have reported that a reduced degree of conversion results in lower flexural strength.[5,36,37] However, most flexural strength studies use bar-shaped specimens whose length (25 mm) requires the use of multiple, overlapping exposures to generate a specimen.[30] In contrast, the current test used specimens that required only a single exposure from the top surface. In addition, these specimens were smaller in diameter than the distal end of the light guide. Fabrication of specimens smaller than the light guide helped to guarantee that test results were more representative of clinical conditions than are values obtained using long, bar-shaped models.

The present design was able to discern differences in flexural strength along the thickness of a composite increment that has clinical relevance. It is known that the ability of composite to polymerize is related to the total amount of energy imparted.[38] However, as light decreases in intensity with composite depth, the duration of exposure must be increased so that each increment receives the same energy and thus has the same potential to polymerize.[39] By producing a bulk composite specimen with uniform flexural properties, there is a maximum resistance for the increment to flex. Less flexure results in lowered potential for fatigue stress of the bond at the cavosurface margin.[17] In addition, because composite is a brittle material, a critical level of stress development causes a small amount of flexure, and the specimen spontaneously fails. The test method was designed to determine the influence of exposure duration needed to accommodate for the

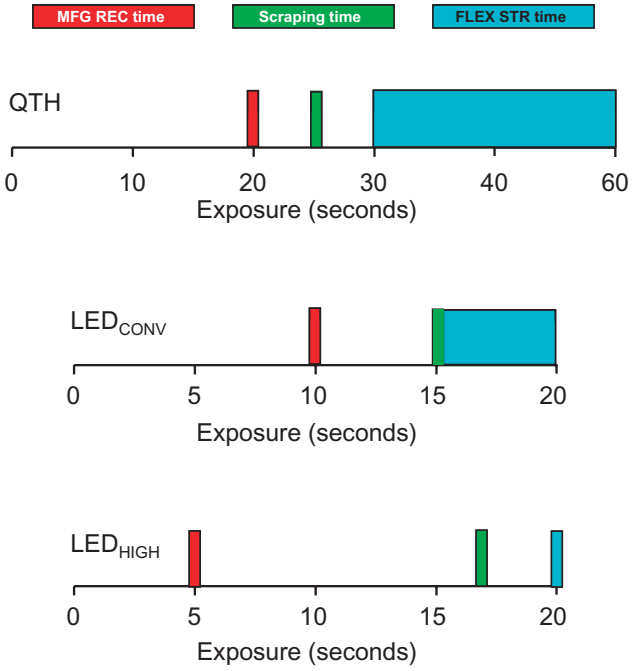

Figure 9. Relationship between manufacturer-recommended exposure duration for a 2.5-mm-thick increment and the optimal exposure value determined using biaxial flexure testing or scraped composite thickness. LED_{CONV} = conventional blue light-emitting diode; LED_{HIGH} = high-intensity blue light emitting diode; MFG REC = manufacturer-recommended; FLEX STR = flexural strength; QTH = quartz-tungsten-halogen.

decrease in light transmission at various depths, so that the resulting product would yield flexural properties similar to those of the top-most increment, which received the greatest amount of irradiant energy.

In addition, the tip-to-composite distance was held at 2 mm, not only for the flexural strength study but also when fabricating composite compule specimens for the scraping test. This distance is more clinically relevant than merely holding the tip directly against the specimen itself, which is commonly done in such studies.

Flexural Strength—Test Results

Data indicate that flexural strength of the composite specimen at depth increases as the exposure duration is lengthened. However, different light-curing units use greatly different exposure durations for optimizing flexural strength at different depths. Factors such as light irradiance, spectral distribution, and beam homogeneity change with tip distance and have an effect on the quantity and quality of photons reaching the top surface.[28,40,41] In addition, the spectral distribution and irradiance are changed by light scattering, absorption, and reflection within the composite, so the character of light available at different composite depths varies as well.[18,19] Thus, lights with different spectral emission as well as differences in power density levels at those different frequencies will result in variation in the extent of polymerization occurring at different composite depths, as seen in the present study (Figure 5). A good example of the effect of these differences is seen in comparing flexural strength values at 2.5 mm, where exposure durations of the different lights were used to provide flexural strength values at that depth that were not different from those at the respective top, irradiated 0.5-mm-thick increment (Figure 7). For the QTH light emitting 602 mW/cm^2, 30 seconds was needed to achieve this goal. However, for the LED_{CONV} unit (emitting near that output value: 593 mW/cm^2), only a 15-second exposure was required to achieve the same result. The difference in effectiveness of the lights is the contributing factor for these results. Although having similar power densities, the LED unit provided higher output values within the spectral region where the

photoinitiator (camphorquinone) has a higher absorbance. In addition, it can be noted that the much greater output value LED_{HIGH} unit requires a greater exposure time (20 seconds) to achieve what the lower-powered LED_{CONV} gave. Differences here cannot be attributed to spectral emissions, as the two lights are quite similar in that pattern. However, they use different tip types, which may result in a difference of power being distributed across the beam. Thus, on a per-second basis, the LED_{CONV} unit proved to be more effective than the equally strong QTH light, and even a much stronger LED unit. However, results measured at different tip-to-composite distances may influence the pattern of test results obtained. Logically, it would seem that the clinician would desire a uniformly performing composite increment that provides minimal flexure upon loading. The test method developed in this research identifies exposure values required to provide such optimal composite performance, and clearly provides meaningful distinctions among the curing light's effectiveness.

Correlation of Depth of Cure (DOC) Among Test Results

When interpreting the correlation among test results, it is important to recognize that scraping depths were estimated to within 1-second increments. However, flexural strength values were limited to the discrete exposure times used: 5-, 10-, or 20-second increments. Thus, although strength values might have indicated a specified exposure duration was needed to provide similar values at 2.5 mm as those observed at the top increment, in actuality, the exposure time could have been between the previous exposure tested that failed to meet this criterion and the subsequent exposure tested that did. Taking this concept into consideration, the optimal exposure time of the QTH for biaxial strength was 30 seconds or more, whereas scraping indicated 25 seconds. However, optimal exposure for the biaxial test could have fallen between the 20- and 30-second time points, which were the only two increments measured. Thus, it is not unreasonable that the scraping test, which bracketed biaxial times, could more precisely locate the optimal exposure time.

For the LED_{CONV} light, optimal performance was found at 15 seconds for both the scraping and biaxial flexure data. For the LED_{HIGH} light, scraping results optimized at 17 seconds, whereas flexure strength was found to require 20 seconds. However, the preceding data point for flexural strength was at only 15 seconds, and the scraping time fell between the two biaxial exposures tested. Thus, in each case, it seems that the optimal exposure duration found using the scraping method occurred either at the same duration found using biaxial flexure or was within the time increment preceding that of the biaxial test. Therefore, a very good correlation was found between the simple scraping method that can be performed in-house and the much more sophisticated and clinically relevant physical property of flexural strength. Also, it is worth noting that, in all cases, the optimal exposure times found using either scraping or flexural strength were longer than those recommended by the manufacturer.

With these results in mind, a clinician could use the simple scraping method to fabricate in-office specimens and generate plots similar to those in the present work that would determine the exposure durations needed to optimize incremental composite performance at the same time minimizing the clinical time taken to generate the desired result. The effect of changes in increased tip-to-composite distances can be easily accommodated for by placing a roll of clear adhesive tape around the prepared compule end so that the distance from the tape end to the composite top surface is set to the value desired. Then, a series of exposures could be made using

that distance, and the corresponding results would be entered into the data enabling the clinician to accurately adjust for changes in light intensity, as the tip is held at different distances from the restorative material during photo curing. All materials and the computer software for generating scraping-exposure plots and for determining optimal exposure durations are readily available in most current clinical practices.

Not all composite materials were tested in this research, nor were a variety of tip-to-composite distances used. However, the authors feel confident that, with the principles demonstrated using the small selection of parameters included in this test, it is not unreasonable to assume such variables would follow the trends shown using the sampling included in this study.

CONCLUSIONS

Within the limitations imposed during this in vitro testing, it may be concluded that:

1. Biaxial flexural strength of composite at depths remote from the top, irradiated surface increase with increasing exposure durations
2. The type and characteristics of light-curing units used affects the exposure duration required to reach similar strength values at composite depth as those achieved at the top, irradiated surface
3. The thickness of composite left after scraping away unpolymerized material can be used as an indicator for optimal performance of composite with respect to exposure duration
4. Manufacturer-recommended exposure duration values are not reliable indicators of optimal composite performance, such as biaxial flexural strength or thickness of residual composite following scraping away of uncured material
5. Exposure durations determined using the simple in-office composite compule-scraping tests are an accurate indicator of optimal composite biaxial flexural strength and allow the clinician to fabricate a custom chairside exposure guide, taking into account the specific composite product and light-curing unit combination available.

CLINICAL IMPLICATIONS

Manufacturer-recommended exposure durations may not provide optimal results, indicating that the clinician must somehow determine this value when fabricating direct, photo-cured composite restorations. The recommended time duration provided is only a single value and does not take into account many clinically relevant issues related to the success of using that value for any specific clinical situation: curing light power density, tip-to-composite distance, spectral output of the emitted light, composite shade and photochemistry, and increment thickness. This research provides clinicians with an easily performed in-office test, using items typically found in most offices, whereby operators can precisely determine optimal exposure times for their given clinical situation. The validity of exposure durations obtained using this method are confirmed in this work by the finding that a much more sophisticated, laboratory test (biaxial flexure strength) provides similar exposure times.

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