©Operative Dentistry, 2016, **41-2,** 200-207

Effect of Tooth-structure Thickness on Light Attenuation and Depth of Cure

NJ Hamlin • C Bailey • NC Motyka
KS Vandewalle

Clinical Relevance

Newer bulk-fill resin composites boast a depth of cure of up to 5 mm, with some manufacturers recommending a trans-tooth photo-polymerization technique. While natural human tooth structure significantly attenuates the irradiance from a dental curing unit, clinically favorable depths of cure can be achieved with the use of trans-tooth curing.

SUMMARY

Newer bulk-fill composites claim a greater depth of cure than conventional resin-based composites. To facilitate complete curing, the manufacturer of SonicFill (Kerr) recommends curing from the occlusal, as well as the buccal and lingual, surfaces of the tooth. The purpose of this study was to quantify the degree of curing light attenuation as it passes through natural tooth structure, and how this attenuation affects the depth of cure of different posterior resin composites. Ten noncarious extracted mandibular third molars were sectioned to produce 5-mm-thick pieces of buccal tooth structure. Sanding 0.5-mm increments from the flattened surface produced 4.5-, 4.0-, 3.5-, 3.0-, 2.5-, 2.0-, and finally 1.5-mm-thick sections. A Bluephase G2 (Ivoclar) curing light with an 8-mm-diameter light guide set on high for 20 seconds was used for measurement of irradiance as it passed through different thicknesses of tooth structure and air. The average irradiance (mW/cm^2) was measured with a MARC-RC Resin Calibrator with a 4-mm-diameter sensor (BlueLight Analytics). To measure depth of cure of a conventional hybrid composite (Herculite Ultra; Kerr) vs a bulk-fill hybrid composite (SonicFill) through varying thicknesses of tooth structure, composites were cured in a 4-mm-

*Nicholas J. Hamlin, PhD, DDS, MS, Resident, AEGD-2, Air Force Postgraduate Dental School, Joint Base San Antonio, Lackland, TX. Current address: Naval Medical Research Unit - San Antonio, Joint Base San Antonio - Fort Sam Houston, TX, USA

Clifton W. Bailey, DDS, director, Senior Training and Education, AEGD-2, Air Force Postgraduate Dental School, Joint Base San Antonio - Lackland, TX, USA

Nancy C. Motyka, DDS, program director, AEGD-2, Air Force Postgraduate Dental School and Consultant to the Air Force Surgeon General for General Dentistry, Joint Base San Antonio - Lackland, TX, USA

Kraig S. Vandewalle, DDS, MS, director, Dental Materials and Research, AEGD-2, Air Force Postgraduate Dental School, Joint Base San Antonio - Lackland, TX, USA and Uniformed Sciences University of the Health Sciences, Bethesda, MD, USA

*Corresponding author: 3650 Chambers Pass, Bldg 3610, JBSA - Fort Sam Houston, TX, 78234; email: nicholas.j.hamlin2.mil@mail.mil

DOI: 10.2341/15-067-L

diameter × 10.25-mm-long split mold according to International Organization for Standardization 4049. A mean and standard deviation was determined per group. Data were analyzed with a one-way analysis of variance (ANOVA)/Tukey test and two-way ANOVA/Tukey test (α=0.05). One-way ANOVA/Tukey found a significant decrease in irradiance based on thickness of tooth structure or distance through air (p<0.001). Two-way ANOVA/Tukey found a significant decrease in depth of cure based on thickness of tooth structure (p<0.001) and on composite type (p<0.001) with no significant interaction (p=0.623). SonicFill had a significantly greater depth of cure than Herculite Ultra.

INTRODUCTION

Light-cured resin-based composites have been around since at least the 1960s, with the first visible light-cured composite placed in 1976.[1] Over the decades, these materials have been refined to improve many of their physical properties, including strength, wear resistance, polishability, and handling. A major limitation of resin-based composites is their relative contraindication in certain posterior restorations, particularly high occlusal load areas, and in cusp replacement. To meet this demand, manufacturers have continued to improve the strength of resin composites by incorporating various sizes and shapes of filler particles, starting with the macrofills, up to today's microfills, nanofills, and nanohybrids.[2] The challenge has been to improve strength while maintaining polishability, handling characteristics, and, while less critical for posterior restorations, relatively good to superior esthetics.

Practitioners desire restorative materials that are easy to use, easy to handle, and polymerize quickly and on demand without sacrificing physical properties. A major limitation of direct posterior composites vs direct amalgam restorations is the technique sensitivity of composite placement. Not only do composites require a dry field, extra steps for enamel and dentin etching, priming, and bonding, but placement of the composite-resin material can be critical. The concern of composite shrinkage, and subsequent cusp deflection, is related to the cavity C-factor and composite placement technique, in either a layered or bulk-fill technique. The maximum incremental thickness has historically been 2 mm. However, restoring deeper preparations with 2-mm increments is time consuming and relatively technique sensitive. Manufacturers have introduced new "bulk-fill" flowable and restorative composites, which reportedly can be cured in increments of 4 mm or greater. Studies evaluating the efficacy of incremental vs bulk filling have been somewhat equivocal, with shrinkage stress and cuspal deflection in some studies but reduced cuspal deflection in others.[3,4] Incremental layering may allow flow during curing with additional free surface area. However, incremental curing allows more maximum polymerization and subsequently more shrinkage stress. Little clinical evidence exists to support one particular composite application method over another.[2] Conventional resin-based composites have moved more toward smaller filler particle size for increased esthetics but higher filler load for strength. In contrast, the newer bulk-fill composites generally require greater translucency to achieve greater depths of cure, thus using lower filler loading with larger particle sizes, resulting in reduced hardness compared with conventional composites.[5,6]

Several bulk-fill composite materials are currently on the market, including the low-viscosity formulations, such as x-tra base (VOCO, Indian Land, SC, USA), SureFil SDR (Dentsply, Milford, DE, USA), Venus Bulk Fill (Heraeus Kulzer, South Bend, IN, USA), and Filtek Bulk Fill Flowable (3M ESPE, St. Paul, MN, USA), as well as high-viscosity formulations such as x-tra-fil (VOCO), Tetric EvoCeram Bulk Fill (Ivoclar Vivadent, Amherst, NY, USA), Filtek Bulk Fill (3M ESPE), and SonicFill (Kerr Corporation, Orange, CA, USA). SonicFill and Filtek Bulk Fill boast a depth of cure of up to 5 mm.[7,8] If the cavity preparation is deeper than 5 mm, the manufacturer suggests placing in two increments. By contrast, Kerr's nanohybrid composite, Herculite Ultra, has a recommended maximum incremental cure of 2 mm.[9]

Unlike most other bulk-fill composite materials that have greater translucency to facilitate penetration of visible light for curing, SonicFill reportedly has translucency similar to that of conventional resin-based composites.[6] The manufacturer suggests a curing time of 20 seconds from the occlusal (or follow curing light manufacturer's instructions) and an additional cure from the buccal and lingual aspects for 10 seconds each.[7] While some light directed from a buccal or lingual direction may directly reach restorative material at the line angles, material at the axial-pulpal line angles will rely on light transmitted through either tooth structure from the buccal or lingual or through several millimeters of composite resin from the occlusal aspect. Although research has been done to characterize the amount of light attenuation through resin-based composites,[10] fiber posts,[11] and glass ceram-

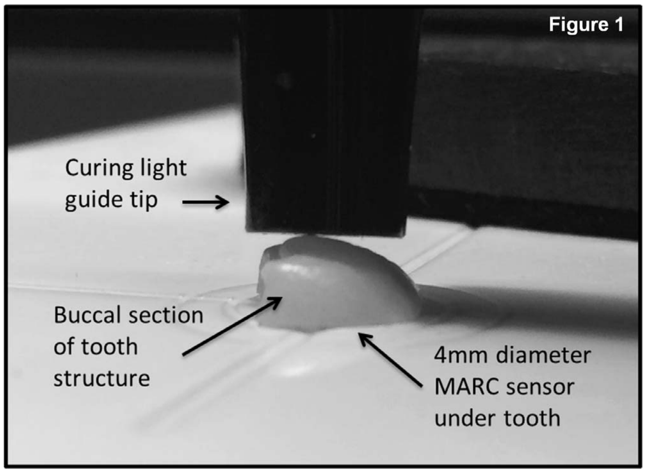


Figure 1. *Measurement of irradiance through tooth structure, with light guide tip directly against maximum convexity of tooth. To measure mean irradiance in air, irradiance was measured at varying distances without tooth structure present, with light guide tip mounted perpendicular and centered on the MARC sensor.*

ics,[12] much less has been done to study light curing through natural tooth structure. In one study by Forsten,[13] two microfilled and one macrofilled composites were exposed with three different curing lights through a 0.8-mm-thick enamel-dentin slab; curing depth was found to be reduced by at least one-third.

The purpose of our study was to test the null hypotheses that natural tooth structure will not significantly attenuate the light from a dental curing unit, and that depth of cure of different resin-based composites will not be affected by curing through tooth structure.

METHODS AND MATERIALS

Sample Preparation

Ten noncarious extracted mandibular third molars were used in this study. The roots were amputated, and the teeth were sectioned to produce 5-mm-thick pieces of buccal tooth structure using an Isomet low-speed saw (Buehler, Lake Bluff, IL, USA). Thickness was measured with a micrometer from the most buccal prominence. The sectioned surfaces were sanded with increasing grits starting with 120 grit, then 320 grit, and finally 600 grit wet/dry sandpaper (Norton, Worcester, MA, USA). After testing, samples were sanded to thinner sections in 0.5-mm increments: 4.5, 4.0, 3.5, 3.0, 2.5, 2.0, and finally 1.5 mm. Orbital sanding paper (120 grit, Diablo, High Point, NC, USA) mounted to the low-speed saw was used for sanding down 0.5-mm increments of tooth, followed by hand sanding with 320- and 600-grit paper. Tooth sections were blotted with a gauze pad to obtain a dry enamel surface and maintain a moist, but not wet, dentin surface, similar to clinical conditions when placing and curing composite-resin restorations.

Irradiance

A Bluephase G2 (Ivoclar Vivadent) curing light with an 8-mm-diameter light guide set on high for a 20-second curing cycle was used for measurement of irradiance from the light as it passed through different thicknesses of tooth structure. The average irradiance (mW/cm^2) from the curing light was measured with a MARC-RC Resin Calibrator (Blue-Light Analytics, Halifax, Nova Scotia, Canada). The most buccal prominence of the tooth samples were centered on the 4-mm-diameter sensor of the MARC-RC Resin Calibrator. The Bluephase G2 curing light was plugged into an electrical outlet to assure a consistent power supply (ie, no battery power under all conditions). The curing light irradiance was measured periodically throughout the study to assure consistent output. The light guide tip was oriented perpendicular and centered on the MARC-RC sensor and directly in contact with the most buccal prominence of the tooth specimen (Figure 1). Irradiance was recorded through each thickness of tooth structure over a 20-second curing cycle using the MARC-RC software. Overall, 10 measurements were made per thickness of tooth structure to include in the statistical analysis. As a control, average irradiance was measured in air over a 20-second curing cycle with the curing light guide tip placed at 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, and 5.0 mm away from the MARC-RC sensor. These distances correspond to the thickness of tooth structure used in the experimental groups and control for reduction in the irradiance due to distance from light guide tip to sensor. Ten measurements per distance were made at each control distance to include in the statistical analysis.

Depth of Cure

To measure depth of cure of a conventional composite (enamel shade A2, Herculite Ultra, Kerr) vs a bulk-fill composite (shade A2, SonicFill, Kerr), composite specimens were cured in a 4-mm-diameter × 10.25-mm-long stainless steel split mold (Sabri Dental Enterprises, Downers Grove, IL, USA). The 4-mm-diameter mold corresponds with the 4-mm-diameter sensor of the MARC-RC Resin Calibrator. A Mylar matrix strip (0.002 inches, Henry Schein, Melville, NY, USA) was placed over the top of the

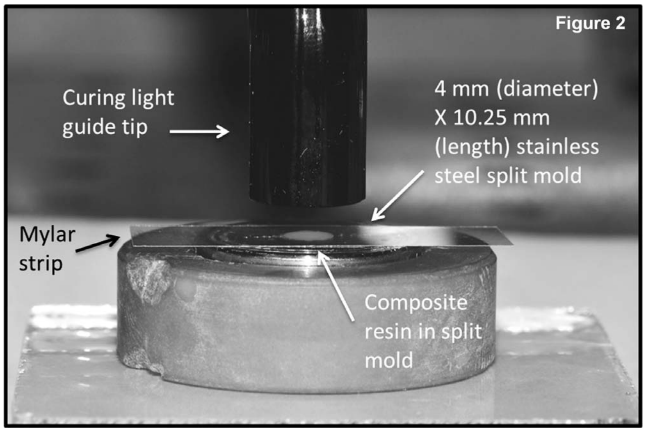


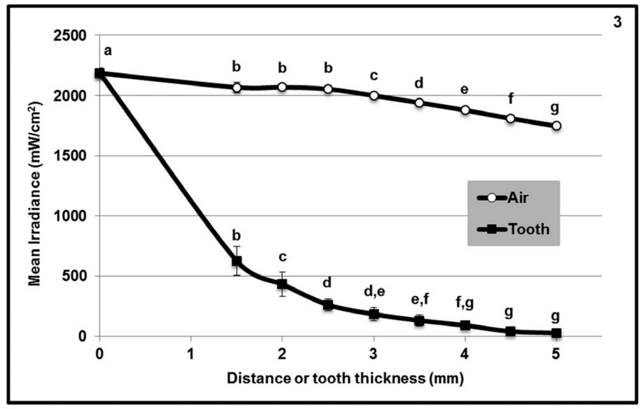
Figure 2. *Measurement of depth of cure at varying distances in air, with light guide tip perpendicular to the composite resin in the stainless steel split mold. To measure depth of cure through tooth structure, buccal sections of tooth at varying thicknesses were placed directly on the Mylar strip, with the light guide tip directly in contact with maximum convexity of tooth.*

split mold, and the curing light was mounted perpendicular to the mold surface. For specimens cured though different thicknesses of tooth structure, the sectioned and sanded surface of the tooth was placed on the split mold with a Mylar strip in between. The curing light guide tip was placed perpendicular to the mold surface and directly against the most buccal prominence. The mold was immediately split apart, and uncured composite was scraped away with a plastic instrument, per International Organization for Standardization (ISO) 4049.[14] The depth of cure was measured with a micrometer (to the nearest 1/100 millimeter), and the value was divided by two to determine depth of cure. For control groups, the curing light was placed directly in contact with the Mylar strip, or at increments of 0.5 mm between 1.5 and 5.0 mm in air, and the composite specimen was cured for 20 seconds on high (Figure 2).

All sectioned tooth specimens were stored at room temperature in 0.5% chloramine-T until use. While testing, specimens were kept at room temperature in distilled water before use. A mean and SD were determined per group.

Data Analysis

One-way analyses of variance (ANOVA) and Tukey post hoc tests were used to examine the effect of tooth thickness or distance through air on mean irradiance. Two-way ANOVA and Tukey post hoc tests were used to examine the effects of composite type and tooth thickness or distance through air on depth of cure.



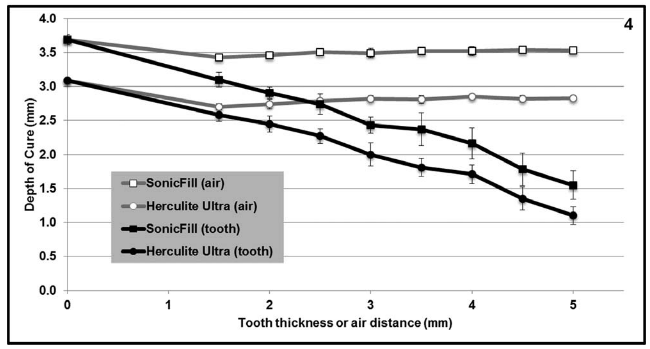


Figure 3. *Mean irradiance (mW/cm²) vs tooth thickness or distance in air (mm) (no tooth structure between light guide tip and MARC-RC sensor). Error bars represent 1 standard deviation above and below the mean. Increments designated with the same letter are not significantly different (p>0.05) per line.*

Figure 4. *Depth of cure (mm) vs tooth thickness or distance in air (mm). Error bars represent 1 standard deviation above and below the mean.*

RESULTS

The one-way ANOVAs with Tukey post-hoc tests found a significant decrease in irradiance based on thickness of tooth structure ($p<0.001$) or on distance through air ($p<0.001$). Figure 3 displays the mean irradiance from the curing light at 0 mm and at half-millimeter increments of distance between 1.5 and 5.0 mm with and without intervening tooth structure. At 0 mm, the mean irradiance from the curing light was 2186 mW/cm^2. A reduction in irradiance was found at increasing distances from the light guide tip to the sensor through air. This reduction ranged from 95% of mean irradiance (2068 mW/cm^2) at 1.5 mm to 80% of mean irradiance (1747 mW/cm^2) at 5.0 mm. The reduction in mean irradiance when light passed through tooth structure was found to range between 28.6% of mean irradiance (625.5 mW/cm^2) through 1.5 mm of tooth structure and 1.2% of mean irradiance (26.7 mW/cm^2) through 5.0 mm of tooth structure.

Two-way ANOVA and Tukey post-hoc tests found significant differences in depth of cure based on thickness of tooth structure ($p<0.001$) and on composite type ($p<0.001$) with no significant interaction ($p=0.623$). Figure 4 displays the mean depth of cure through tooth structure or air. Significant differences in depth of cure were found based on thickness of tooth structure except between the 3.0- and 3.5-mm increment. SonicFill had a significantly greater depth of cure compared with Herculite Ultra. A two-way ANOVA found significant differences in depth of cure based on distance through air ($p<0.001$) and on composite type ($p<0.001$); however, there was a significant interaction ($p=0.003$). Between 1.5 and 5 mm, the depth of cure for both SonicFill and Herculite Ultra cured through air remained relatively unchanged.

DISCUSSION

On the basis of our results, we reject the null hypothesis and accept the alternate hypothesis that there is a significant decrease in the amount of irradiance based on thickness of tooth structure or on distance through air. To our knowledge, this is the first study that has used a specifically designed curing light spectrophotometer, the MARC-RC Resin Calibrator, to quantify the mean irradiance transmitted through natural tooth structure. Figure 3 shows the exponential drop in mean irradiance as light passes through increasing thickness of tooth structure. A previous study using a handheld digital radiometer and 1.0-mm incremental thicknesses of dentin found a similar drop in transmitted light energy, as expressed as a percentage of maximum, ie, that measured without tooth structure between the light guide tip and detector.[15] We also reject the null hypothesis that there is no difference in the depth of cure of two different resin-based composites when cured through different thicknesses of tooth structure or through the equivalent distance in air.

Our rationale for investigating depth of cure when light is passed through tooth structure comes directly from the manufacturer's recommendation for the curing of bulk-fill composites, specifically SonicFill by Kerr, which recommends a 20-second cure from the occlusal, followed by 10-second cures from the buccal and lingual aspects of the tooth.[7] In our study, we chose to use a 20-second curing cycle under all conditions to facilitate direct comparison across experimental and control conditions. Figure 4 shows that, with a single curing cycle of 20 seconds and 0 mm from light guide tip to resin composite, SonicFill had a mean depth of cure of 3.69 ± 0.07 mm, which agrees with other recently published studies using ISO 4049.[16,17] Kerr claims a depth of cure of up to 5 mm for SonicFill, but to achieve this depth of cure, we need to follow the manufacturer's instructions and also cure from buccal and lingual aspects (through tooth structure).

The largest tooth in a buccal-lingual direction on average is the maxillary first molar, with a cervical diameter of ~10.0 mm and a crown diameter of ~11.0 mm.[18] If we consider a class II composite preparation in a maxillary first molar, the gingival/pulpal floor buccal-lingual dimension of one-third the tooth's diameter would be approximately 3.5 mm. This would leave approximately 3.5 mm of tooth structure in both the buccal and lingual directions at the most prominent diameter of the tooth. On the basis of the results from this study, the depth of cure expected for SonicFill with 3.5 mm of tooth structure between the light guide tip and composite would be 2.37 ± 0.24 mm (Figure 4). If cured from both the buccal and lingual directions, a total depth of cure in the buccal-lingual direction of 3.5 mm would be possible. However, as stated above, we set up our *in vitro* conditions such that all curing cycles were for 20 seconds, whereas the manufacturer recommends only 10 seconds. Considering an occlusal depth of cure without intervening tooth structure of 3.69 mm, in addition to the 2.37 mm from both the buccal and lingual directions, a total depth of cure of 5.0 mm as measured from the occlusal surface is possible.

A study by Campodonico and others[19] prepared extracted human teeth with a slot-shaped mesial-occlusal-distal cavity of 4 mm in depth and 4 mm in width, with a mean wall thickness of tooth structure of 2.39 mm. They placed a bulk-fill hybrid composite (x-tra fil, VOCO) and a nanocomposite (Filtek Supreme Plus, 3M ESPE) using incremental and bulk-fill techniques. In addition, specimens with bulk-filled Filtek Supreme Plus were also cured with a trans-tooth illumination technique. They used a simultaneous (two curing units) technique in which they cured for 20 seconds from the buccal and lingual and then 20 seconds from the occlusal. Their results with Filtek Supreme Plus showed that, with the bulk-fill technique, Knoop hardness values decreased beyond a 2-mm depth of cure compared with the incremental placement technique, thus supporting incremental placement with traditional light curing techniques. However, with additional curing using trans-tooth illumination, the authors found that a drop in hardness did not occur until a depth of 3 mm, and the trans-tooth curing technique yielded higher hardness values at a depth of 1.5 mm compared with restorations placed with the incremental technique. Their study did not test trans-tooth bulk-curing of x-tra fil, a hybrid composite marketed for bulk placement. The instructions for use for x-tra fil call for a 10- to 20-second occlusal curing cycle for an increment of up to 4 mm and also recommend an additional curing cycle from an “oral or vestibular” approach, when accessible.[20]

While Herculite Ultra is not marketed as a bulk-fill composite and the manufacturer states that increments should be placed no more than 2.0 mm in depth,[9] our results show that, whereas Herculite Ultra has a statistically significant reduction in depth of cure compared with SonicFill (Figure 4), the values we found, although less than that of the bulk-fill composite, were greater than 2.0 mm in depth when curing through up to 3.0 mm of tooth structure. It should be noted that achievable depth of cure alone is not the only factor to consider when using a resin-based composite material in either a bulk-fill or incremental-placement technique. The cavity configuration, or C-factor, and polymerization shrinkage of the resin composite can affect the stresses on the cavity preparation walls and the integrity of the resin-tooth interface. With respect to light-cured composite-resins, however, marginal adaptation has not been shown to differ significantly between either incremental placement with occlusal cure, bulk-fill with occlusal cure, or bulk-fill with trans-tooth curing in different hybrid bulk-fill and conventional nanocomposites.[19,21]

We observed a gradual and significant decline in mean irradiance with increasing distance in air (Figure 3), from just over 2000 mW/cm^2 at 1.5 mm to approximately 1750 mW/cm^2 at 5.0 mm. However, the change in depth of cure in either Herculite Ultra or SonicFill did not decrease to the same degree with increasing distance through air (Figure 4). We would expect that with increasing distances from the curing light tip to composite resin, there would be a decrease in the amount of light energy delivered to the composite resin;[22,23] however, the decrease found here is modest. At a 5.0-mm distance in air, 1750 mW/cm^2 mean irradiance delivered over a 20-second curing time gives 35 mJ/cm^2 of total energy. At a 1.5-mm distance in air, 2000 mW/cm^2 mean irradiance delivered over a 20-second curing time gives 40 mJ/cm^2 of total energy. Our data do not show a significant difference in depth of cure through air with either 35 or 40 mJ/cm^2 of total energy delivered to either Herculite Ultra or SonicFill. Perhaps shorter curing cycles and greater distance in air between the curing light tip and the composite resin are needed to demonstrate change in depth of cure. Within our experimental parameters, curing light guide tip to composite-resin distance was not the significant variable, whereas the attenuation of light through tooth structure was significant.

When evaluating depth of cure through air, the two-way ANOVA revealed a statistically significant interaction between distance in air and composite type. It can be noted in Figure 4 that with Herculite Ultra, there is little difference in depth of cure with the light guide tip 1.5 mm away versus curing through 1.5-mm-thick tooth structure. Additionally, there is a statistically significant decline in depth of cure at 1.5 mm in air, and then an increase in depth of cure at 2.0 mm, although mean irradiance was not statistically different at these points (Figure 3). More research is needed to better interpret these more subtle findings and better determine their potential clinical significance.

There are several limitations to the current study. The first is that we used a single dental curing light (Bluephase G2, Ivoclar Vivadent) under all conditions. We also investigated a single bulk-fill composite (SonicFill, Kerr) and a single conventional composite (Herculite Ultra, Kerr), both with a single shade (A2). While the purpose of this study was a preliminary investigation into the affect of tooth structure on trans-tooth curing, we cannot draw any conclusions as to how other bulk-fill or conventional composites would perform under the same conditions, nor how the results would change with other curing lights. Each curing light on the market has a unique light emission spectrum and power. Combined with each light's available light guide tips, different collimation, distal light guide tip diameter, and a unique distribution of emitted light across the light-guide tip,[24] different curing lights would be expected to perform differently.

A second limitation of this *in vitro* study is that our conditions are designed to be as close to ideal as possible. We start with a baseline mean irradiance and depth of cure based on the light guide tip in direct contact with the resin composite material (only a Mylar strip between the two). We also oriented the light guide tip directly perpendicular to the MARC-RC Resin Calibrator sensor, as well as to the top surface of the stainless steel split mold. Such conditions of ideal distance and angulation of the curing light guide tip to the restorative material is rarely possible *in vivo*. Although it is known that distance and angulation are critical for maximum and ideal resin composite photo-polymerization,[23,25] several factors make this clinically difficult. Interference of matrix bands, oral anatomy, limited opening by the patient, curing light design, and perhaps, most importantly, variable light-curing technique by the dentist or assistant will all affect the quantity of delivered light to the composite resin and in turn affect the total energy delivered.[22] Such clinical limitations require consideration of additional curing time and/or additional curing cycles to achieve ideal photo-polymerization. It has been found that manufacturer recommendations of curing times for photo-initiated composite resins are typically not adequate.[26] Therefore, in our study, it is fair to compare our ideal conditions and results with the manufacturer's recommendations, bearing in mind that clinical conditions will necessitate adjustments compared with more ideal *in vitro* studies and manufacturer recommendations.

A final significant limitation of our study is that we used a single approach to measure depth of cure, the uncured composite resin scrape test.[14] Although the reduction in mean irradiance was very significant with increasing tooth thickness (Figure 3), the reduction in depth of cure, by our measure, was not as dramatic (Figure 4). It is possible that while the scraped thickness test suggests the depth at which an adequate depth of cure has occurred, these data do not quantify the physical properties of the cured composite resin at different depths. However, it has been shown previously that the scraped composite test is well correlated with more sophisticated flexural strength tests.[26] In contrast, another study evaluated Knoop hardness values in composite resin restorative materials placed in bulk with a trans-tooth light curing approach vs incremental placement and cured from the occlusal only and found that hardness values were lower in the bulk-filled samples.[27]

CONCLUSIONS

Within the limits of this study, these data show a significant decrease in mean irradiance and composite resin depth of cure when curing through natural tooth structure compared with curing through air. Although the decrease in mean irradiance through the tooth structure was significant, the corresponding decrease in depth of cure in both a bulk-fill composite (SonicFill) and a conventional hybrid composite (Herculite Ultra) were affected to a much lower degree. Our data indicate that trans-tooth curing of both bulk-fill and conventional composites may aid in the polymerization of resin within deeper areas of the tooth, resulting in a greater depth of cure in both composite types. Further studies are needed to investigate the mechanical properties of resin composite that is cured with a trans-tooth technique.

Regulatory Statement

This study was conducted in accordance with all the provisions of the human subjects oversight committee guidelines and policies of Wilford Hall Ambulatory Surgical Center / Institutional Review Board in Lackland, Texas. The approval code issued for this study is FWH20140106N (406289-1).

Conflict of Interest

The authors have no proprietary, financial, or other personal interest of any nature or kind in any product, service, and/or company that is presented in this article.

(Accepted 30 April 2015)

REFERENCES

1. Rueggeberg FA (2011) State-of-the-art: Dental photocuring—A review *Dental Materials* **27(1)** 39-52.
2. Ferracane JL (2011) Resin composite—State of the art *Dental Materials* **27(1)** 29-38.
3. Park J, Chang J, Ferracane J, & Lee IB (2008) How should composite be layered to reduce shrinkage stress: incremental or bulk filling? *Dental Materials* **24(11)** 1501-1505.
4. Kwon Y, Ferracane J, & Lee I (2012) Effect of layering methods, composite type, and flowable liner on the polymerization shrinkage stress of light cured composites *Dental Materials* **28(7)** 801-809.
5. Ilie N, & Hickel R (2009) Investigations on mechanical behaviour of dental composites *Clinical Oral Investigations* **13(4)** 427-438.
6. Bucuta S, & Ilie N (2014) Light transmittance and micromechanical properties of bulk fill vs. conventional resin based composites *Clinical Oral Investigations* **18(8)** 1991-2000.
7. Kerr Corporation (2011) SonicFill™ sonic-activated, bulk fill composite directions for use. Retrieved online June 17, 2014 from: http://www.kerrdental.com/cms-filesystem-action?file=/kerrdental-products-dfu/2011_SonicFill_[NA].pdf
8. 3M ESPE (2014) Filtek™ bulk fill posterior restorative instructions for use. Retrieved online February 13, 2015 from: http://multimedia.3m.com/mws/media/976404O/filtek-bulk-fill-posterior-instructions-for-use-western-europe.pdf
9. Kerr Corporation (2014) Herculite® Ultra nanohybrid composite restorative instructions for use. Retrieved online June 17, 2014 from: http://www.kerrdental.com/cms-filesystem-action?file=KerrDental-Products-DFU/dfu-herculiteultra79465%20rev3.pdf
10. Musanje L, & Darvell BW (2006) Curing-light attenuation in filled-resin restorative materials *Dental Materials* **22** 804-817.

11. Ho Y-C, Lai Y-L, Chou I-C, Yang S-F, & Lee S-Y (2011) Effects of light attenuation by fibre posts on polymerization of a dual-cured resin cement and microleakage of post-restored teeth *Journal of Dentistry* **39(4)** 309-315.

12. Flury S, Lussi A, Hickel R, & Ilie N (2014) Light curing through glass ceramics: Effect of curing mode on micromechanical properties of dual-curing resin cements *Clinical Oral Investigations* **18(3)** 809-818.

13. Forsten L (1984) Curing depth of visible light-activated composites *Acta Odontologica Scandinavica* **42(1)** 23-28.

14. ISO Standards (2009) ISO 4049 Dentistry: Polymer-Based Restorative Materials *Geneve: International Organization for Standardization* **4th edition** 1-28.

15. Price RBT, Murphy DG, & Dérand T (2000) Light energy transmission through cured resin composite and human dentin *Quintessence International* **31(9)** 659-667.

16. Garcia D, Yaman P, Dennison J, & Neiva GF (2014) Polymerization shrinkage and depth of cure of bulk fill flowable composite resins *Operative Dentistry* **39(4)** 441-448.

17. Benetti AR, Havndrup-Pedersen C, Honoré D, Pedersen MK, & Pallesen U (2015) Bulk-fill resin composites: Polymerization contraction, depth of cure, and gap formation *Operative Dentistry* **40(2)** 190-200.

18. Ash MM, & Nelson SJ (2003) *Wheeler's Dental Anatomy, Physiology, and Occlusion* **8th edition** Saunders, St. Louis MO.

19. Campodonico CE, Tantbirojn D, Olin PS, & Versluis A (2011) Cuspal deflection and depth of cure in resin-based composite restorations filled by using bulk, incremental and transtooth-illumination techniques *Journal of the American Dental Association* **142(10)** 1176-1182.

20. VOCO GmbH (2010) x-tra fil light-curing, posterior filling material instructions for use. Retrieved online January 11, 2015 from: http://www.voco.com/en/products/_products/x_tra_fil/x-tra_fil_22spr_049.pdf

21. Idriss S, Habib C, Abduljabbar T, & Omar R (2003) Marginal adaptation of class II resin composite restorations using incremental and bulk fill placement techniques: An ESEM study *Journal of Oral Rehabilitation* **30(10)** 1000-1007.

22. Price RBT, McLeod ME, & Felix CM (2010) Quantifying light energy delivered to a class I restoration *Journal of the Canadian Dental Association* **76(2)** a23.

23. Price RB, Shortall AC, & Palin WM (2014) Contemporary issues in light curing *Operative Dentistry* **39(1)** 4-14.

24. Vandewalle KS, Roberts HW, & Rueggeberg FA (2008) Power distribution across the face of different light guides and its effect on composite surface microhardness *Journal of Esthetic and Restorative Dentistry* **20(2)** 108-118.

25. Mahn E (2013) Clinical criteria for the successful curing of composite materials *Clinical Journal of Periodontics, Implantology, and Oral Rehabilitation* **6(3)** 148-153.

26. Rueggeberg FA, Cole MA, Looney SW, Vickers A, & Swift EJ (2009) Comparison of manufacturer-recommended exposure durations with those determined using biaxial flexure strength and scraped composite thickness among a variety of light-curing units *Journal of Esthetic and Restorative Dentistry* **21(1)** 43-61.

27. Lazarchik DA, Hammond BD, Sikes CL, Looney SW, & Rueggeberg FA (2007) Hardness comparison of bulk-filled/transtooth and incremental-filled/occlusally irradiated composite resins *Journal of Prosthetic Dentistry* **98(2)** 129-140.