Effect of light-curing time on light-cure/post-cure volumetric polymerization shrinkage and regional ultimate tensile strength at different depths of bulk-fill resin composites

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The aim of this study was to investigate volumetric polymerization shrinkage (VS), using swept-source optical coherence tomography (SS-OCT), of bulk-fill composites with different light-curing strategies; immediately after light-irradiation and after 24 h, and to evaluate their regional ultimate tensile strength (UTS) at different curing depths. The immediate VS after photo-polymerization decreased when the curing light-curing time was reduced from 20 to 10 to 5 s. On the other hand, their VS values after 24 h significantly increased due to the post-cure polymerization, resulting in similar VS values at all the light-curing times. Five seconds light-curing decreased the regional UTS of resin composites after the 24 h period compared with the 10 and 20 s light-curing regimes; therefore, the remarkable progress of post-cure polymerization after light-curing for a short time would not lead to an improvement in the mechanical properties of resin composites. The influence of the light-curing time on the curing depth was dependent upon the bulk-fill composite material.

Keywords: Bulk fill, Volumetric shrinkage, Depth of cure, Optical coherence tomography, Ultimate tensile strength

INTRODUCTION

Light-cured resin composites have been widely used as a direct filling material for esthetically restoring loss of tooth structure. Their physical properties, such as compressive and tensile strength, elastic modulus, polymerization shrinkage, contraction stress and degree of conversion, play significant roles in the clinical success of resin composite restorations, and light irradiation protocols affect them¹⁻³. When filling and light-curing conventional resin composites in deep cavities, several increments should be placed because their appropriate curing depths are up to 2 mm depth⁴. Additionally, this incremental filling technique can reduce contraction stress of resin composite to cavity walls by minimizing the volume of resin composite cured at one time⁵. However, incremental placement is a time-consuming procedure.

Recently, a new category of resin composites “bulk-fill composite” has been introduced to simplify the filling procedure. Generally, increasing the volume of resin composite, which is placed in a cavity, would cause greater contraction stress at the cavity walls, depending upon the c-factor. The contraction stress of resin composite

can lead to cusp displacement and gap formation at the interface between the tooth and restoration. Gaps and lack of integrity at the tooth-composite interface would compromise the clinical prognosis of the restoration because they could cause bacterial micro-leakage, secondary caries and hypersensitivity⁶. However, manufacturers claim that bulk-fill composites can be bulk-filled and light-cured in cavities up to 4 mm in depth with low volumetric polymerization shrinkage (VS), resulting in low contraction stress.

Many studies on bulk-fill composites have been published on bond strength⁷, gap formation⁸, cuspal deflection^{9,10}, mechanical properties¹¹⁻¹³, degree of conversion¹¹⁻¹⁴, depth of cure^{15,16}, polymerization shrinkage^{13,15,16}, contraction stress^{11,13,16}. The polymerization shrinkage of resin composites has been investigated by linear or volumetric measurement using various methods; dilatometer^{17,18}, gas pycnometer¹⁹, buoyancy method¹³, modified linometer^{20,21}, bonded-disk method²², the use of a strain gauge²², and digital video-imaging method²³. Their studies have demonstrated that the polymerization shrinkage of resin composites occurs rapidly after the start of light-irradiation and continues even after the end of the light-irradiation. As long as

there are activated free radicals and reactants present after the primary light-cure phase, the polymerization process will continue. Some studies have reported that post-cure polymerization continued up to or beyond 24 h after light-irradiation^{14,24}. Additionally, it has been reported that composite specimens with a low level of polymerization after the primary light-curing phase generated greater post-cure polymerization^{14,24}. Recently, non-contact 2D and 3D imaging methods such as micro-computed tomography^{10,25} and optical coherence tomography^{26,27} have been employed to investigate the sealing performance of resin composite in cavities. Swept-source optical coherence tomography (SS-OCT) can obtain 2D and 3D cross-sectional images of teeth and periodontal tissues in a non-invasive and non-destructive way, and analyze the behavior of restorative materials inside the cavity in real time^{26,28}. Therefore, this method would enable the VS of resin composite in cavities to be investigated during light-irradiation, and 24 h later or more.

For bulk-fill composites, investigation of the curing depth is important because it usually refers to the filling thickness of a resin composite that is adequately cured. Raman micro spectroscopy can directly evaluate the curing depth of resin composites by measuring the degree of conversion at the different depths^{11,24}. On the other hand, the microhardness test can indirectly evaluate the curing depth because microhardness values at different depths within a resin composite specimen reflect the degree of conversion²⁹. However, their values cannot be used to compare the degree of conversion between different resin materials, because these are

strongly influenced by filler type, size and/or loading. Measurement of regional ultimate tensile strength (UTS) of resin composites using the microtensile test is useful for evaluating the curing depth of resin composite and comparing the mechanical properties of different resin composite materials³⁰.

Most of the published studies have reported polymerization shrinkage data a short time after light-irradiation. The polymerization shrinkage of resin composites occurring during post-cure polymerization was reported to be quite appreciable^{17,18,31}. However, it is unclear whether post-cure polymerization would affect the mechanical properties of resin composites. The aim of this study was therefore to investigate the VS of bulk-fill and conventional composites using SS-OCT immediately after light-curing and after 24 h, and to investigate their regional UTSs at different depths.

MATERIALS AND METHODS

Study materials

Three bulk-fill composites; Filtek Bulk Fill Flowable (FBF), Beautiful Bulk Flowable (BBF), Estelite Bulk Fill Flow (EBF) and one conventional flowable composite, Estelite Flow Quick (EFQ), were used in this study (Table 1).

Volumetric shrinkage measurement

1) Specimen preparation

A rubber mold (thickness of 5 mm) with a standardized cylinder-shaped hole (diameter of 3 mm) was prepared, and a 1 mm thick glass plate was placed at the bottom

Table 1 Resin composite materials used in this study

Material Type	Shade	Composition	Manufactures' curing time (s) Curing depth (mm)	Manufacturer
Estelite Bulk Fill Flow [EBF]	Universal	Filler contents/ 56 vol% 70.0 wt% New organic inorganic hybrid filler, supra nano spheroidal filler (SiO ₂ -ZrOs), Bis-GMA, TEGDMA, BisMPEPP, CQ, Radical-Amplified Photopolymerization initiator	10 4	Tokuyama Dental
Filtek Bulk Fill Flowable [FBF]	Universal	Filler contents/ 42.5 vol% 64 wt% ytterbium trifluoride filler with range of particles sizes from 0.1 to 5.0 microns, zirconia/silica with a particle size range of 0.001 to 3.5 µm, Bis-GMA, UDMA, Bis-EMA, Procrlyat resins	20 4	3M ESPE
Beautifill Bulk Flowable [BBF]	Universal	Filler contents/ 51.0 vol% 73.0 wt% Fluoro-alumino-silicate glass, Bis-GMA, UDMA, Bis-MPEPP, TEGDMA, Reaction initiator, Others	20 4	SHOFU INC
Estelite Flow Quick [EFQ]	CE (Inc)	Filler contents/ 53 vlo% 71.0 wt% Silicazirconia filler, silica-titania filler, Bis-MPEPP, TEGDMA, UDMA, CQ, Radical-Amplified Photopolymerization initiator	20 2	Tokuyama Dental

of the mold. Before placement, the surface of the glass plate was treated with a silane coupling bonding agent; a mixture of Clearfil Photobond (Kuraray Noritake Dental, Tokyo, Japan) and Clearfil Porcelain Bond activator (Kuraray Noritake Dental) followed by light-curing for 10 s. The tested composites were placed into the mold in bulk. After placement, the restoration in the hole was checked using SS-OCT (OCT-2000, Santec, Komaki, Japan) for any over and under filling of the resin materials and/or any internal voids. Then the resin composites were light-cured using a halogen light-curing unit (Optilux501, Kerr, Middleton, WI, USA) with the power density of 600 mW/cm² for 5, 10, and 20 s by placing the tip of the light source on the glass plate at the bottom of resin composite.

2) SS-OCT optical observation of surface displacements
The swept-source OCT system was used to monitor the free surface displacements at the upper surface of the resin composites after light-curing. In this system, the center wavelength is 1,330 nm (bandwidth 110 nm) with a 30-kHz sweep rate. The optical resolution is 20 µm transversally and 12 µm axially in air. The laser beam scans the object in X and Z dimensions. Collected backscattered light from the sample is returned to the system, digitized in time scale, and analyzed in the Fourier domain to form a depth-resolving scan (A-scan) at each point. A serial set of A-scans along a certain section creates a row data file of back-scattered signal intensity (B-scan) and a 2-dimensional cross-sectional (2D) image²⁶⁾.

The handheld scanning probe connected to the SS-OCT was set at a fixed distance (5 cm) over the specimen with the scanning beam oriented 90° with respect to the top surface of the mold. SS-OCT 2D scans were obtained immediately after light-curing. Six cross-sectional images were acquired at 0°, 30°, 60°, 90°, 120°, 150° planes across the specimen by rotating the SS-OCT beam. The filled specimens were stored in a dry and dark condition at 22°C for 24 h and then scanned by SS-OCT in the same manner. To replicate the imaging location each time, the

specimen was marked with a pen and placed in the same orientation as previous scans.

3) Measuring volumetric shrinkage on the SS-OCT image

On the SS-OCT images imported to image analysis software (ImageJ v1.51, Wayne Rasband, NIH, Bethesda, MD, USA), seven points (a, b, c, d, e, f, g) were set with the interval of 0.5 mm at a line referred from the upper surface of the mold (Fig. 1). The distance (A, B, C, D, E, F, G) in the vertical direction to the surface of the light-cured resin composite at each point (a, b, c, d, e, f, g) was measured on six SS-OCT images (0°, 30°, 60°, 90°, 120°, 150°). From the data of these distances, the VS of the resin composite at each measurement period (immediately after curing, after 24 h) was calculated from the following equation.

$$v1 = 0.5 \times 0.5 \times \pi \times \left(\frac{C+D}{2} + \frac{D+E}{2} \right): \text{Amount of volumetric shrinkage at central area on each SS-OCT image.}$$

$$v2 = (1.0 \times 1.0 - 0.5 \times 0.5) \times \pi \times \left(\frac{B+C}{2} + \frac{E+F}{2} \right): \text{Amount of volumetric shrinkage at middle area on each SS-OCT image.}$$

$$v3 = (1.5 \times 1.5 - 1.0 \times 1.0) \times \pi \times \left(\frac{A+B}{2} + \frac{F+G}{2} \right): \text{Amount of volumetric shrinkage at peripheral area on each SS-OCT image.}$$

$$v = v1 + v2 + v3: \text{Total amount of volumetric shrinkage on each SS-OCT image.}$$

$$\text{VS (Volumetric shrinkage of the one sample)} = \frac{v(0^\circ) + v(30^\circ) + v(60^\circ) + v(90^\circ) + v(120^\circ) + v(150^\circ)}{6}: \text{Volumetric shrinkages } (v(0^\circ), v(30^\circ), v(60^\circ), v(90^\circ), v(120^\circ), v(150^\circ)) \text{ on the } 0^\circ, 30^\circ, 60^\circ, 90^\circ, 120^\circ \text{ and } 150^\circ \text{ SS-OCT images.}$$

Fig. 1 Measurement point and distance for obtaining VS.

Ultimate microtensile strength test

1) Specimen preparation

A cavity (depth of 5 mm and diameter of 8 mm) was prepared in a ABS resin block ($1 \times 1 \times 1 \text{ cm}^3$). An impression of the cavity was taken using putty and regular type hydrophilic vinyl polysiloxane impression material (Exahiflex, GC, Tokyo, Japan). Forty replicas of the cavity model were fabricated by filling the impression mold with dual-cure resin composite (ESTE CORE, Tokuyama Dental, Tokyo, Japan), and light-cured with the halogen light-curing unit for 60 s, and finally cured with a laboratory light-curing unit (α -light II, J. Morita, Tokyo, Japan) for 10 min to ensure complete polymerization of the resin composite. The models were then stored for one week in water before their use.

The internal surface of the cavity was superficially abraded using an abrasive point (Shofu, Kyoto, Japan) mounted in a low-speed handpiece under water spray, and prepared without any bonding procedure. All the external surfaces, except the cavity opening side of the model, were covered with black paper tape to prevent light passing through the composite walls during light-curing. All the cavities were then bulk filled with one of the resin composites without surface treatment. The upper surface of each specimen was covered with a plastic strip and pressed with a glass slide to squeeze out any excess resin composite. The specimens were then light-cured with a halogen light-curing unit with power density of 600 mW/cm^2 for 5, 10, and 20 s by placing the tip of the light source at the top of the cavity. The specimens were then stored in 37°C water for 24 h.

2) Regional UTS measurement

After 24 h storage, each specimen was attached to the arm of a low speed diamond saw (Isomet, Buehler,

Lake Bluff, IL, USA) and sectioned in the middle region parallel to the axial cavity wall twice, to obtain 2 mm-wide slabs. One slab was then fixed at its base and serially sliced five times starting from the top surface of filled resin composite to harvest 5, 0.65 mm-thick beams representing five depth levels of the restoration. The beams were then trimmed to an hour-glass shape with a width of 0.65 mm at their narrowest region. The cross-sectional area of each beam was measured using a digital caliper (Mitutoyo CD15, Mitutoyo, Kawasaki, Japan). The ends of the beams were glued to a testing device in a table-top testing machine (EZ-SX, Shimadzu, Kyoto, Japan) using cyanoacrylate glue (Model Repair II Blue, Dentsply-Sankin, Tokyo, Japan) and subjected to a tensile force at a crosshead speed of 1 mm/min (Fig. 2). UTS was calculated by dividing the fracture load by the surface area.

Statistical analysis

The VS and UTS data were analyzed by three-way ANOVA and *t*-test with Bonferroni correction. All statistical tests were performed at a 95% level of confidence.

RESULTS

Volumetric shrinkage

The means and standard deviations of the VS of resin composites are shown in Table 2. Three-way ANOVA revealed that VS were significantly different according to the resin composite materials, light-curing time, and measurement period ($p < 0.0001$). There was a significant interaction in the VS data among resin composite materials, light-curing time and measurement time ($p = 0.043$). For VS measured immediately after light-

Fig. 2 Schematic view of the method used in this study.

Table 2 The means and standard deviations of volumetric shrinkage (%)

Immediately after curing				
Light-curing time (s)	EBF	FBF	BBF	EFQ
20	1.54 (0.16) ^{aAB}	1.78 (0.15) ^{aA}	1.09 (0.19) ^{aC}	1.37 (0.24) ^{aB}
10	1.46 (0.06) ^{aA}	1.43 (0.14) ^{bA}	0.77 (0.14) ^{bC}	1.07 (0.17) ^{bB}
5	1.13 (0.09) ^{bA}	1.14 (0.22) ^{cA}	0.57 (0.08) ^{bB}	0.80 (0.13) ^{cB}
After 24 h				
Light-curing time (s)	EBF	FBF	BBF	EFQ
20	1.96 (0.22) ^{aB}	2.10 (0.16) ^{aAB}	1.62 (0.21) ^{aB}	2.46 (0.32) ^{aA}
10	1.97 (0.10) ^{aAB}	1.78 (0.16) ^{aBC}	1.43 (0.33) ^{aC}	2.35 (0.12) ^{aA}
5	2.28 (0.33) ^{aB}	1.74 (0.23) ^{aC}	1.43 (0.33) ^{aC}	2.84 (0.30) ^{aA}

Means (S.D); $n=5$.

Same small letters within columns indicates no significant difference for individual material at each measurement time.

Same capital letters within rows indicates no significant difference for individual curing time at each measurement time.

Table 3 UTS of the investigated resin composites (MPa)

Material	Depth (mm)	Light curing time		
		20 s	10 s	5 s
EBF	1	99.0 (10.3) ^{aA}	103.0 (12.1) ^{aA}	85.0 (14.5) ^{aB}
	2	100.9 (9.8) ^{aA}	104.4 (12.9) ^{aA}	89.1 (11.5) ^{aB}
	3	102.5 (15.6) ^{aA}	97.6 (12.3) ^{abA}	84.1 (12.1) ^{aB}
	4	99.6 (8.7) ^{aA}	95.4 (11.9) ^{abA}	79.8 (13.8) ^{abB}
	5	82.0 (11.5) ^{bA}	84.8 (16.2) ^{bA}	65.0 (14.1) ^{bB}
FBF	1	91.1 (12.4) ^{aA}	95.3 (12.1) ^{aA}	69.4 (10.6) ^{aB}
	2	96.2 (13.0) ^{aA}	96.5 (11.3) ^{aA}	70.5 (6.6) ^{aB}
	3	94.1 (11.9) ^{aA}	92.6 (9.7) ^{aA}	68.1 (7.1) ^{aB}
	4	90.6 (12.7) ^{aA}	96.3 (9.2) ^{aA}	65.4 (7.0) ^{aB}
	5	83.8 (11.9) ^{aA}	83.3 (9.3) ^{aA}	58.9 (13.5) ^{aB}
BBF	1	90.4 (11.2) ^{aA}	92.7 (10.3) ^{aA}	81.7 (5.6) ^{aA}
	2	81.4 (11.2) ^{aA}	84.8 (9.4) ^{abA}	86.0 (8.1) ^{aA}
	3	89.0 (12.4) ^{aA}	88.1 (5.9) ^{abA}	72.1 (8.6) ^{bB}
	4	81.4 (14.3) ^{aA}	78.5 (8.1) ^{bcA}	63.5 (5.2) ^{bB}
	5	80.8 (13.1) ^{aA}	70.9 (10.8) ^{cA}	54.9 (9.0) ^{cB}
EFQ	1	98.1 (12.9) ^{aA}	99.0 (14.8) ^{aA}	79.6 (11.2) ^{aB}
	2	100.4 (12.5) ^{aA}	102.4 (11.4) ^{aA}	76.2 (8.6) ^{abB}
	3	92.4 (7.4) ^{aA}	99.7 (7.8) ^{aA}	63.9 (18.3) ^{bcB}
	4	86.1 (14.4) ^{abA}	83.6 (6.1) ^{bA}	49.8 (7.7) ^{cB}
	5	74.9 (14.5) ^{bA}	67.6 (11.8) ^{cA}	29.6 (13.8) ^{dB}

Means (S.D); $n=10$.

Same small letter within columns indicates no significant difference for individual materials and light curing times.

Same capital letter within rows indicates no significant difference for individual materials and depths.

curing, there was no significant interaction between the resin composite materials and light-curing time ($p=0.48$), while, for VS measured after 24 h there was a significant interaction between the resin composite materials and light-curing time ($p=0.045$).

When the light-curing time was 20 s, VS measured

immediately after light-curing were in the order of BBF, EFQ, EBF, and FBF. For all the resin composites, the VS measured immediately after light-curing decreased with a reduction in the light-curing time, in which 5 s light-curing significantly decreased VS compared with 20 s light-curing ($p<0.05$). Additionally, for FBF, BBF

and EFQ, 10 s light-curing also significantly decreased VS compared with 20 s light-curing ($p < 0.05$), while for EBF, there was no significant difference in VS between 10 and 20 s light-curing times ($p > 0.05$). On the other hand, the 24 h period significantly increased the VS of all the resin composites for all the light-curing times ($p < 0.05$), in which VS measured after 24 h were in the order, BBF, EBF, FBF and EFQ. For bulk-fill resin composites (EBF, FBF, BBF), there was no significant difference in VS measured after 24 h between all the light-curing groups ($p > 0.05$), while for the conventional resin (EFQ), 5 s light-curing resulted in significantly higher VS than the 10 and 20 s light-curing durations ($p < 0.05$).

Ultimate microtensile strength test

The means and standard deviations of the regional UTS for each resin composite at each depth are shown in Table 3. Three-way ANOVA revealed that the UTS were significantly different according to the resin composite materials, light-curing time and depth ($p < 0.0001$, respectively). There were no significant interactions in the UTS data among the resin composite materials, light-curing time and depth ($p = 0.40$), and there was a significant interaction between the resin composite materials and light-curing time ($p < 0.0001$), between the resin composite materials and depth ($p < 0.0001$), while there was no significant interaction between light-curing time and depth ($p = 0.053$).

For EBF, FBF, and EFQ, 5 s light-curing resulted in significantly lower UTS than 10 and 20 s light-curing at each depth ($p < 0.05$), while for BBF, the UTS of the superficial layer (1–2 mm) was not significantly different between all the light-curing times ($p > 0.05$). The curing depths of the bulk-fill resin composites (EBF, FBF, BBF) were deeper than that of the conventional resin composite (EFQ). The curing depth of EFQ decreased with the reduction in light-curing time. However, for the bulk-fill resin composites, the effect of light-curing time on their curing depth varied among the materials. For FBF, there was no significant difference in UTS between 1–5 mm depths at each light-curing time ($p > 0.05$). For BBF, UTS with 20 s light-curing time did not differ significantly between 1–5 mm depths ($p > 0.05$), while the curing depth decreased with a reduction of light-curing time. For EBF, there was no significant difference in UTS between 1–4 mm depths at each light-curing time ($p > 0.05$), while UTS at 5 mm depth decreased significantly.

DISCUSSION

SS-OCT has been developed based on the concept of low-coherence interferometry, which permits real-time non-invasive visualizing of internal biological and biomaterial structures. The light beam with infrared light waves used in SS-OCT is projected over a scattering sample, and backscattered light is transformed into a signal intensity that reveals depth-resolved information about the scattering and reflection of the light in the sample.

The signal is converted into computed software and can be reconstructed as a cross-sectional image of the sample with high-resolution, and the surface profile of the sample is clearly visualized as a bright line on the SS-OCT image when the sample has a different refractive index from air. Recently, SS-OCT has been used for the detection of caries, tooth fractures, and secondary caries at the restoration-tooth interface *in vivo* and *in vitro*^{6,28}. Additionally, some studies have demonstrated that SS-OCT can be used for the quantitative measurement of gaps between resin composite and cavity walls³² and observation of real-time gap progression²⁶. A recent study using SS-OCT observation, reported that internal gap formations in resin composite restorations were correlated with the shrinkage parameters of resin composites³⁹.

Generally, the polymerization shrinkage of resin composite develops with an increase in the degree of conversion thereby improving its mechanical properties^{33,34}. In this study, the VS of the resin composites was calculated by measuring the distances in the vertical direction between the surface of the resin composite before and after light-curing on the SS-OCT image. In the present study, the VS of resin composites measured immediately after light-curing was around 0.5–2%, which was in agreement with previous studies³⁵. Additionally, for all the composites, VS measured immediately after light-curing decreased with a reduction in the light-curing time, and in particular, the 5 s light-curing group had significantly lower VS than the 20 s light-curing group. The reduction of the VS values would indicate a lower degree of conversion in the resin composites by light-irradiation. On the other hand, after a 24 h period, the VS of all the resin composites significantly increased, resulting in similar VS values between all the light-curing groups. Some studies using Raman micro spectroscopy have demonstrated that the degree of conversion of resin composites exhibited a significant increase after 24 h compared to those immediately after light-curing^{14,24}. It is well known that after light-curing, the degree of conversion of resin composite increases and the post-cure polymerization mostly occurs during the first 24 h after light-curing³⁶. Post-cure polymerization occurs because some portions of the radicals generated during light-irradiation are trapped within the heterogeneous network and can persist for extended periods³⁷. With the progress of the time, trapped radicals can encounter pendant groups, resulting in additional conversion. Additionally, in composite samples with initially lower degrees of conversion, a higher amount of un-reacted radicals allows for the increased mobility to make contact with other reactive species in the polymer network, leading to further promotion of post-cure polymerization, whereas in highly polymerized samples, reactive sites are immobilized in the polymer network^{38–40}. The reason for the remarkable increase in VS in the 5 s light-curing group may be due to the fact that post-cure polymerization was more pronounced in resin composites with an initial lower degree of conversion.

In this study, regional UTS of resin composite at each depth (1–5 mm) were measured using the microtensile test for evaluation of the mechanical properties after a 24 h period. Five seconds light-curing gave significantly lower UTS in all the resin composites than 10 and 20 s light-curing, except for BBF in the superficial layer (1–2 mm depths). These results would indicate that, when light-curing is performed for 5 s, post-cure polymerization might not lead to an improvement in the mechanical properties of resin composites. Light-curing for a sufficient time would seem to be important for obtaining the higher mechanical properties of resin composites even if post-cure polymerization could be further generated with short duration light-curing.

Additionally, measurement of regional UTS at each depth is a useful method for evaluating the curing depth of resin composites, whereby their values are strongly influenced by the polymerization behavior of resin matrix compared with the measurement values of the microhardness test³⁰. In this study, the curing depth of bulk-fill resin composites (EBF, FBF, BBF) was deeper than that of the conventional resin composite (EFQ). The curing depth of EFQ decreased with a reduction in the light-curing time. However, for the bulk-fill resin composites used in this study, the effect of light-curing time on their curing depths varied. The effects of light-curing on resin composite are dependent upon several factors; such as the light translucency of resin composite, the monomer composition and type, concentration of initiator, inhibitor and accelerator⁴¹. In general, in order to increase the curing depth, bulk-fill resin composites display a higher translucency than conventional resin composites⁴². Higher translucency can be achieved by a reduction in filler content⁴³. FBF produced deeper curing depth than the other bulk-fill resin composites, except for BBF in the 20 s light-curing group. For FBF, in each light-curing group, there were no significant differences in UTS between 1–5 mm depths; therefore, the curing depth was not affected by the light-curing time. However, in the 5 s light-curing group, the superficial layers (1–2 mm depths) exhibited significantly lower UTS than those in the 10 and 20 s light-curing groups. These results might be strongly influenced by the higher translucency of FBF because FBF has a slightly lower filler fraction compared to the other resin composites¹². On the other hand, for BBF, the UTS with 20 s light-curing did not significantly differ between 1–5 mm depths, whereas the curing depth decreased with a reduction in the light-curing time. However, the UTS of the superficial layers (1–2 mm depths) were not affected by light-curing time, which was not the case for FBF. These results would indicate that in the superficial layers (1–2 mm depths), BBF could sufficiently polymerize even when the light-curing time was short. These differences between FBF and BBF might be due to differences in translucency and in concentration of photo-initiator/catalyst.

For EBF, at each light-curing time, there were no significant differences in UTS between 1–4 mm depths, while UTS decreased significantly at 5 mm depth.

These results indicate that EBF had a lower curing depth than FBF and BBF. However, the curing depth was not affected by light-curing time. Additionally, for EBF, VS measured immediately after light-curing was not significantly different between the 10 and 20 s light-curing times although for other resin composites, there was a significant difference in VS between the 10 and 20 s light-curing groups. These results indicate that EBF could be sufficiently polymerized with 10 s light-curing at 1–4 mm depths. EBF uses radical-amplified photopolymerization initiator (RAP) technology, in which energy from the initial stage of CQ excitation by light is transferred to the radical amplifier⁴⁴. The radical amplifier is subsequently excited, and then allowed to decompose to produce radical-amplifier-derived radicals. These radicals act as the polymerization initiator and react with monomers to generate polymers, producing the curing effect, which can lead to lower concentration of CQ and shorter light-curing time. This may be the reason why there was no significant difference in VS between the 10 and 20 s light-curing time. On the other hand, although EFQ also uses RAP technology, 10 s light-curing resulted in lower VS than 20 s light-curing. Presumably, there might be difference in the concentration of CQ between EFQ and EBF.

The light transmission characteristics as well as the mechanical properties of resin composites are influenced by filler load, type, size and shape⁴². Generally, higher filler load can decrease the polymerization shrinkage of resin composite⁴⁵. EBF and EFQ contain nano spherical silica-zirconia fillers. On the other hand, FBF contains nanocluster fillers and BBF contains surface pre-reacted glass-ionomer (S-PRG) filler. These fillers would have different optical properties, leading to various light scattering behaviors within the resin composites. Therefore, they might affect the curing depth and polymerization shrinkage of resin composites in addition to the effect of light-curing time. Further research is necessary to determine the optical effect of fillers on polymerization behavior of resin composites.

CONCLUSIONS

Within the limitations of this study, it was concluded that the VS of resin composites measured immediately after light-curing decreased with a reduction in the light-curing time (20, 10 and 5 s). On the other hand, for all the resin composites, the VS values significantly increased after 24 h due to the post-cure polymerization, resulting in similar VS values at all the light-curing times. A short light-curing time of 5 s decreased the regional UTS of resin composites after a 24 h period compared with the 10 and 20 s light-curing protocols; therefore, even with post-cure polymerization, a short light-curing time would not lead to an improvement in the mechanical properties of resin composites. For the tested bulk-fill resin composites, the influence of light-curing time on the curing depth was dependent upon the material, whereas the curing depth of the conventional resin composite was affected by light-curing time.

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