Effect of resin thickness and light-curing irradiance on the hardness and depth of cure of short fiber-reinforced resin composite

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Abstract. This study analyzed the effect of short fiber-reinforced resin composite (SFRC) thickness and light-curing irradiance on the depth of cure. A total of 24 specimens of SFRC (EverX Posterior™) were made and divided into two different groups based on thickness: 4 and 5 mm (n = 12), formed into a cylindrical shape with a diameter of 6 mm. Each group was divided into two subgroups cured by different light-emitting diode (LED) curing units with different irradiances: 1000 and 1200 mW/cm² (n = 6). Each specimen was cured for 20 s with a 2-mm light-curing distance. The depth of cure was measured by calculating a Vickers hardness ratio of the bottom to the top surfaces of specimens (%). Data were analyzed statistically by one-way ANOVA tests, followed by post hoc Fisher’s least significant diameter (LSD) tests. The depths of cure in the 4-mm thickness groups cured by 1000 and 1200 mW/cm² light-curing irradiance were 79.46 ± 0.85% and 80.74 ± 0.95%, respectively, compared to 49.41 ± 0.47% and 61.65 ± 0.77%, respectively, in the 5-mm thickness groups. The results showed significant differences (P < 0.05) in the depth of cure in all groups tested. It can be concluded that SFRC thickness and light-curing irradiance have a significant effect on the depth of cure.

1. Introduction

In dentistry, resin composites with fiber as reinforcement have been used widely recently to restore a cavity on a high-stress-bearing area, such as a dentin substitute (substructure), because of its similarity to the dentin structure and better physical and mechanical properties compared to particulate resin composites (PRCs) [1–3]. Fiber-reinforced resin composites (FRCs) are classified based on fiber length (continuous and discontinuous) and orientation [4]. A new type of short randomized fiber-reinforced resin composite (SFRC; EverX Posterior™) consists of bisphenol A-glycidyl methacrylate (Bis-GMA), triethylene glycol dimethacrylate (TEGDMA), and polymethyl methacrylate (PMMA) as resin matrix. This combination of crosslinked and linear polymers forms a matrix called a semi-Interpenetrating Polymer Network (semi-IPN), which provides good adhesive bonding [2]. This SFRC also consists of inorganic particulate filler and E-glass fibers as reinforcement to improve the mechanical properties. The short and randomly oriented fibers provide an isotropic reinforcing effect, which also provide the same value of mechanical properties in all directions [1,4,5].
On the basis of the manufacturer’s claim, SFRC has similar or even greater fracture toughness compared to dentin. Therefore, it can strengthen the dentin structure biomimetically. The manufacturer also claims that SFRC can be bulk-filled up to 4 mm into the cavity and has a depth of cure (DoC) of 4 mm based on the ISO 4049 method if polymerized with a light-curing irradiance of 700 to 1200 mW/cm² for 10 to 20 s [6]. DoC can be measured using several techniques, such as calculating the hardness ratio of the bottom to the top surfaces, using the degree of conversion, with optical microscopy, using Vickers microhardness profile, and using the ISO 4049 method [7]. On the basis of the latest study, an optimal DoC cannot be achieved with other techniques, except the ISO 4049 method [8–10]. The specimens of those studies were polymerized with a light-curing irradiance of 800 mW/cm² for 20 s. Meanwhile, for bulk-fill materials, the DoC measurement result based on ISO 4049 was overestimated compared to the measurement using other techniques [11]. DoC is significant because of the increased risk of clinical failure caused by decreased physical and mechanical properties. Furthermore, cytotoxicity can occur if the materials are not well-polymerized. Several factors can affect the value of DoC, such as light-curing distance and irradiance, curing time, post-cure period, resin composite thickness and color, and filler size and distribution [12]. When determining how to achieve an optimal DoC according to the manufacturer’s statement, light-curing irradiance may be a factor that can affect the DoC based on the manufacturer’s suggestions of light-curing irradiance range.

This study analyzed the effect of SFRC thickness and light-curing irradiance on the DoC by measuring the bottom to the top surface hardness ratio of SFRC.

2. Materials and Methods
A total of 24 cylindrical specimens of SFRC (EverX Posterior™; GC Corp., Japan. Batch number: 1703293) with a diameter of 6 mm were prepared and divided into two groups based on thickness: 4 and 5 mm (n = 12). Specimens were pressed for 30 s under a glass microscope slide with a load of 1 kg. Each group was divided into two subgroups that were cured by different light-emitting diode (LED) curing units with different irradiances: 1000 mW/cm² (LITEX™ 695, Dentamerica, Inc., San Jose, CA, USA) and 1200 mW/cm² (DTE® LUX E including Radiometer; Woodpecker, Guilin, China; n = 6). The light source irradiance was measured using a radiometer (Bluephase® Meter II; Ivoclar Vivadent, Schaan, Liechtenstein) three times before being used to verify the irradiance of each unit, and the irradiance was calculated as the average of these three readings. Each specimen was then cured under a mylar strip for 20 s, and polymerization was performed by positioning a light guide tip 2 mm from the top surfaces of the specimens using a plastic stopper to standardize the distance. After polymerization, the specimens were then wet-stored in an incubator at 37°C for 24 h to prevent ambient light from causing additional post-curing polymerization.

After 24 h of storage, the Vickers hardness number (VHN) was determined on the top and bottom surfaces of each specimen using a microhardness testing machine (Zwick-Roell Microhardness Tester, Ulm, Germany). Nine randomized indentations were made on each surface (top and bottom) under a 200 g load and a dwell time of 15 s. DoC was measured by calculating the Vickers hardness ratio of the bottom to the top surface of each specimen (%).

Mean and standard deviation values were calculated for each group in each test. Data were explored for normality testing using Saphiro–Wilk tests and then analyzed statistically by one-way ANOVA tests, followed by post hoc Fisher’s least significant difference (LSD) tests.

3. Results
The mean surface hardness values of the top and bottom surfaces and DoC of SFRC at various thicknesses and light-curing irradiances are shown in Table 1.
Table 1. Mean surface hardness values and DoC of SFRCs at various thicknesses and light-curing irradiances

| Thickness (mm) | Light-Curing Irradiance (mW/cm²) | Surface Hardness Mean ± SD (VHN) | DoC ± SD (%) |
|----------------|----------------------------------|----------------------------------|--------------|
|                |                                  | Top                              | Bottom       |              |
| 4 mm           | 1000                             | 57.96 ± 0.27⁸⁸                   | 46.06 ± 0.39³³ | 79.46 ± 0.85⁸³ |
|                | 1200                             | 58.37 ± 0.24³³                   | 47.13 ± 0.64⁷⁷ | 80.74 ± 0.95³³ |
| 5 mm           | 1000                             | 57.87 ± 0.29³³                   | 28.59 ± 0.22⁷⁷ | 49.41 ± 0.47³³ |
|                | 1200                             | 58.30 ± 0.23³³                   | 35.85 ± 0.50⁷⁷ | 61.65 ± 0.77⁷⁷ |

The same superscript letters in vertical columns indicate no significant difference (P > 0.05). Different superscript letters in vertical columns indicate a significant difference (P < 0.05).

Table 1 shows the differences in Vickers hardness values and DoC between all groups tested. In the 4-mm thickness groups, the top surface hardness values of specimens polymerized with 1000 mW/cm² light-curing irradiance (57.96 ± 0.27 VHN) were significantly lower than those in the 1200 mW/cm² irradiance group (58.37 ± 0.24 VHN). Similarly, the 5-mm thickness groups showed significantly lower top surface hardness values in the 1000 compared to the 1200 mW/cm² irradiance groups (57.87 ± 0.29 vs. 58.30 ± 0.23 VHN, respectively). Note that, in Table 1, the same superscript letters on the groups with the same light-curing irradiance indicate no significant difference in top surface hardness values between the groups polymerized with the same light-curing irradiance. For the bottom surface, there were significant differences between all groups tested, and the hardness value decreased with increasing SFRC thickness and decreasing light-curing irradiance.

4. Discussions
One factor that can affect the DoC of resin composites is total energy (J/cm²). Total energy is obtained by multiplying the light-curing irradiance (mW/cm²) and curing time (s) [12]. In this study, the curing time was the same in all groups (20 s), so the total energy was 20 and 24 J/cm² for the groups polymerized with 1000 and 1200 mW/cm² light-curing irradiance, respectively. At the top surface of the specimens, there was no difference in total energy received by resin composites with different thicknesses. This statement is related to our result showing no significant difference in top surface hardness value of groups polymerized by the same light-curing irradiance because the amount of total energy received by the top surfaces was the same. Different amounts of total energy received would affect the hardness value of the top surface significantly (Table 1). In addition, the degree of polymerization in crosslinked polymeric systems has a potentially large role in determining the properties of resin composites, including surface hardness. Factors that can affect the crosslinking density were light-curing irradiance, curing time, and light-curing distance [14,15]. In this study, there was no difference in curing time and light-curing distance set between all groups tested; therefore, the dominant factor in this study was the light-curing irradiance. Therefore, the top surface of SFRC polymerized with 1200 mW/cm² light-curing irradiance (total energy of 24 J/cm²) may have formed a higher crosslinking density than the top surface in the 1000 mW/cm² irradiance group (total energy of 20 J/cm²), resulting in higher surface hardness values.

For the bottom surface, several factors can affect the light transmission reaching the deepest part of the resin composite, including resin composite thickness (distance from the top to the bottom surface), size, shape, and amount of filler particles, as well as the total energy received. The light transmission from the light-curing unit received by the resin composite decreases as the light moves further down the resin thickness, increasing in the distance traveled, resulting in inability to reach the deepest
portion of the resin composite [14]. In theory, the traveling light will be scattered at the conversion between the matrix and filler particles because of the different refractive indexes [11,16]. The size, shape, and number of filler particles also affect the amount of light scattered [14,15]. The increase in volume of the resin composite will be followed by an increase in the number of filler particles. This causes more light to be scattered, thus decreasing the amount of energy received, causing the resin composite not to fully polymerize, and the hardness of the bottom surface will decrease. These factors can affect the amount of total energy received in the lower surface, decreasing the total energy received and hardness of the bottom surface.

In this study, DoC was obtained by measuring the hardness ratio of the bottom to the top surfaces of SFRC. Therefore, the value of DoC was highly dependent on that ratio. The hardness ratio of the bottom to the top surface must exceed 80% to be considered as having adequate polymerization [13]. On the basis of our results, the bar diagram in Figure 1 lowers as the SFRC thickness increases and the light-curing irradiance decreases. A DoC value of >80% was achieved in the 4-mm thickness SFRC group polymerized with 1200 mW/cm² light-curing irradiance (total energy 24 J/cm²), compared to 79.46% in the 1000 mW/cm² irradiance group. For the 5-mm thickness SFRC group, the DoC values were 61.65% and 49.41%, respectively. Both of these results were lower than those in the 4-mm thickness groups. Therefore, to restore a cavity with more than 4 mm in thickness, it is more preferred to build the resin composites incrementally to achieve optimal polymerization for better clinical success of the restoration. The inability to achieve an optimal DoC will result in a worse clinical outcome, such as poor wear resistance, formation of a secondary carious lesion, and cytotoxicity toward the vital tooth structure [12,17].

To restore a deep cavity, several factors, such as high light-curing irradiance, long curing time, and type of light source, can raise the temperature of pulp tissues [18]. In clinical application, the main indications of SFRCs are to reinforce restorative materials used for direct composite restorations, especially in large posterior cavities, including three surfaces or more; cavities with missing cusps; deep cavities, including class I, II, and endodontically treated teeth; cavities after amalgam replacement; and cavities where onlays and inlays would also be indicated [6]. Considering those indications, a high amount of total energy used to achieve an optimal DoC may have an impact on increasing the temperature of pulp tissues. This is due to the placement of SFRC restoration as a substructure that is very close to the pulp tissue. Clinical research has shown that irreversible damage may occur at a temperature rise of 5.5°C to 11°C on the roof of the pulp chamber. For restoration using the FRC (EverStick C&B) with a thickness of 2 mm cured with 1000 mW/cm² irradiance for 20 s (total energy 20 J/cm²), there was a temperature rise of only 3.76 ± 0.73 °C, which means that irreversible damage to pulp tissues would not occur [18]. Resin composites may be 100% polymerized at 2 mm thickness; meanwhile in our study, the DoC obtained by SFRC at 4 mm thickness did not reach 100%. This is also related to the hardness value of SFRC at 4 mm thickness, which decreased approximately 20% from the top to the bottom surfaces. This also means that the amount of total energy received by the lower surfaces decreased compared to that of the top surfaces. Therefore, there may be a temperature rise, but it would not be harmful enough to cause irreversible damage.

5. Conclusion
SFRC thickness and light-curing irradiance can affect the DoC of SFRC significantly ($P < 0.05$). DoC became lower as the SFRC thickness increased and the light-curing irradiance decreased. The optimal DoC (>80%) was obtained with a 4 mm SFRC thickness cured with 1200 mW/cm² light-curing irradiance for 20 s (total energy of 24 J/cm²). This amount of irradiance was still within the manufacturer’s range suggestions for the LED curing unit.
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