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ORIGINAL ARTICLE

Light polymerization during cavity filling: influence of total energy density on shrinkage and marginal adaptation

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Abstract The aim of the study was to evaluate the marginal adaptation and shrinkage stress development of a micro hybrid restorative composite as a function of energy density. Linear displacement and shrinkage forces were measured with custom-made devices for energies of 4,000, 8,000, 16,000 and 32,000 mJ/cm^2 at a constant power density of 800 mW/cm^2. Marginal adaptation of composite restorations cured with the same energy density was evaluated before and after mechanical loading with 300,000 cycles at 70 N. The group "4,000 mJ/cm^2" showed the lowest shrinkage force [2.9(0.2) kg] and linear displacement [23.5(0.7) µm] but led to the worst marginal adaptation after loading [46.4(23.5) %CM] probably due to under-curing. When the maximum energy of 32,000 mJ/cm^2 was applied, a slight increase in shrinkage forces [3.6(0.2) kg and 29.2(0.8) µm], and a slight decrease in marginal adaptation after loading [75.4(11.5) %CM] were observed, but these changes were not significantly different in comparison to groups cured with energies of 8,000 and 16,000 mJ/cm^2. For the resin composite tested in this study, no differences in marginal adaptation could be detected above the energy threshold of 8,000 mJ/cm^2.

Keywords Curing protocol · Radiant exposure · Linear shrinkage · Polymerization force · Marginal integrity

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Introduction

Volumetric contraction during light cured polymerization of methacrylate based dental composites generates internal stresses within the materials mass [1]. If the material is adhesively fixed to a tooth cavity, these stresses will be transferred to the margins and can negatively affect marginal integrity [2]. To minimize the effects of polymerization shrinkage, different composite materials, restorative techniques, light curing protocols and curing devices have been proposed in the last decades [3–6]. Several studies have evaluated the effect of energy density variations on properties such as depth of cure [7], degree of conversion [8], micro hardness [9], fracture toughness [10], Raman spectroscopy [11] and elastic modulus [12]. A direct influence of the level of energy on degree of cure and mechanical properties has been observed. This means that the higher the energy density delivered by the curing unit, the higher the degree of cure and mechanical properties of the restorative material [13].

Nevertheless, the minimum acceptable energy density necessary to promote a stress-resistant adhesion at the tooth composite interface remains unknown. In addition, this is one of the few factors that can be easily modified by the clinician in the daily practice, as the level of energy is the result of exposure time × the irradiance delivered by the curing unit. In this respect, it may be of interest to evaluate how different energy densities applied to a model of a class V composite restoration affect marginal adaptation and also shrinkage stress development due to polymerization. Shrinkage forces represent, in fact, the potential loads to which an adhesive interface can be subjected and may negatively affect the integrity of the restoration margins.

Therefore, the aim of the present study was to evaluate the marginal adaptation and shrinkage stress development

as a function of energy density. The research hypotheses to test were that (1) light curing with different energy would affect the quality of marginal adaptation before and after fatigue conditions and that (2) light curing with different energy would affect shrinkage stress development.

Materials and methods

A three step adhesive system (Syntac Classic, batch number j04289, IvoclarVivadent, Schaan, Liechtenstein) and a hybrid restorative composite (Tetric A2, batch number k01012, IvoclarVivadent, Schaan, Liechtenstein) were used for the restoration of all cavities from the four test groups ($n = 8$). Thirty-two caries-free human molars stored in 0.1 % thymol solution were used for the experiment within 2 months following extraction. Selected molars had complete apex, were free of caries and had similar dimensions. After scaling and pumicing, the teeth were mounted on custom-made specimen holders with the buccal surface parallel to the support using a cold-polymerizing resin (Technovit 4071, Heraeus Kulzer GmbH, Wehrheim, Germany) and then randomly assigned to four experimental groups (Table 1).

One non-bevelled round standardized cavity with half of the margins located in enamel and half in dentin was prepared in the cervical portion of the tooth with 80 μm diamond burs (Diatech Dental, Coltène-Whaledent, Altstätten, Switzerland) under continuous water-cooling. The dimensions of the cavities were 4 mm in diameter and 2 mm in depth; this cavity size corresponded approximately to a *C* factor of 3. Before insertion of the composite, the adhesive system was applied and light cured for 20 s. Then the composite was inserted into the cavity in one layer and light-cured according to the different curing protocols (Table 1). One level of irradiance was used in all groups (800 mW/cm^2) with irradiation times of 5, 10, 20 and 40 s. This resulted in a final energy density (level of irradiance multiplied by exposure time) of 4,000, 8,000, 16,000 and 32,000 mJ/cm^2, respectively. A calibrated halogen light source was used (Swiss Master Light, Serial No. M1053, EMS, Nyon, Switzerland) at a constant relative power density output of 800 mW/cm^2 previously verified with a radiometer (Curing Radiometer Model 100, Serial No. 134089, Demetron Research Corp. Danbury, CT, USA). In additional, light-curing irradiance was monitored with the "test" window, located in the device, before light curing of each sample. Immediately after polymerization, and prior to water storage, the restorations were polished using flexible aluminium oxide discs (SofLex PopOn, 3M ESPE AG, Seefeld, Germany) with decreasing (from coarsest to finest) grain sizes.

Table 1 Description of the experimental groups

Groups (mJ/cm^2)	Irradiance (mW/cm^2)	Irradiation time (s)
32,000	800	40
16,000	800	20
8,000	800	10
4,000	800	5

The final polishing was assessed using an optical microscope under 12× magnification and corrected if necessary. After storage in the dark in a 0.9 % saline solution at 37 °C for 1 week, the restored teeth were fixed perpendicular to their holders and submitted to 300,000 cycles at 70 N of loading force applied to the centre of the restoration in a loading chamber filled with room tempered tap water [14]. The axial loading force was exerted at a 1.5 Hz frequency, following a one-half sine wave curve. Restorations were contacted by antagonist artificial cusps made of stainless steel, the hardness of which is similar to natural enamel (Vickers hardness: enamel = 320–325, steel = 315). The diameter of the metal cusps was of 4 mm. Immediately after completion of the polishing procedure (before loading) and after loading, the teeth were cleaned with rotating brushes and tooth paste. Then impressions with a polyvinylsiloxane material (President light body, Coltène-Whaledent, Altstätten, Switzerland) were made of each restoration. Subsequently, gold-coated epoxy replicas were prepared for the computer assisted quantitative margin analysis in a scanning electron microscope (XL20, Philips, Eindhoven, Netherlands) at 200× magnification. The marginal quality, expressed in percentages of continuous margins (%CM), was reported for the total marginal length at each interval, i.e. before and after loading. A continuous margin was reported when no marginal opening or gap was observed in the adhesive interface between resin composite and tooth substrate.

Measurements for linear displacement induced by polymerization shrinkage was carried out with a custom-made measuring device [15], similar to the one developed by Gee et al. [16]. A standardized amount of the same composite as used for cavity fillings was placed on the aluminium platelet of the device. Then the composite was flattened with a glass plate to a test height of 1.5 mm and a surface area of 50.2 mm^2 at both top and bottom of the sample. Polymerization in groups 32,000, 16,000, 8,000 and 4,000 mJ/cm^2 was carried out for 40, 20, 10 and 5 s, respectively. The same light-curing device with 800 mW/cm^2 power density, as mentioned above, was used for these tests. The vertical movement of the diaphragm caused by polymerization shrinkage of the composite was detected for 180 s by an infrared sensor with an accuracy of 100 nm and a sampling frequency of 5 Hz.

Measurements for polymerization shrinkage force were carried out with a custom-made measuring device similar

to the one developed by Gee et al. [16]. The upper part consisted of a semi-rigid load cell (PM 11-K, Mettler, Greifensee, Switzerland) to which was screwed a metal cylinder of 8 mm diameter. In this way a semi-rigid configuration of a cavity with a *C* factor of 3 was simulated. The cylinder was coated with the composite, which was compressed at a distance of 1.5 mm and a surface area of 46 mm^2 at both top and bottom of the sample, onto a glass plate attached to the base of the device. The surfaces of the metal cylinder and of the glass plate were sandblasted with 50 μm aluminium oxide particles (Microetcher, Danville Engineering, Danville, CA, USA) at 2 bars pressure and silanized (Monobond S, IvoclarVivadent, Schaan, Liechtenstein). Polymerization in groups 32,000, 16,000, 8,000 and 4,000 mJ/cm^2 was carried out for 40, 20, 10 and 5 s, respectively. The same light curing with 800 mW/cm^2 power density, as mentioned above, was used for these tests. Forces generated during polymerization shrinkage were detected for 180 s by means of the load cell at a sampling frequency of 5 Hz. The data were fed on-line by means of an A/D converter using custom-made software to a personal computer (Macintosh II fx, Apple computer, Cupertino, CA, USA) and stored on its hard disc. Eight measurements for linear displacement and eight for shrinkage force were performed on each group and their mean values were plotted.

Comparison of the data, reported as mean(SD) from the four groups in terms of %CM, linear displacement and shrinkage force was performed with one-way ANOVA (SPSS for Windows). A paired *t* test was used to compare the groups before/after loading, Duncan post hoc test was run to detect differences among groups. The level of confidence was set to 95 %.

Results

The least score of linear displacement [mean(SD)] was observed in the group light cured with an energy density of 4,000 mJ/cm^2 [23.5(0.7) μm]. Significant differences in linear shrinkage were observed between the groups cured with an energy density of 8,000 mJ/cm^2 [26.7(1.1) μm], 16,000 mJ/cm^2 [27.8(1.1) μm] and 32,000 mJ/cm^2 [29.2(0.8) μm], as shown in Table 2. Regarding polymerization force, the group light cured with an energy density of 4,000 mJ/cm^2 exhibited significantly lower force values [2.9(0.2) kg] with respect to groups cured with energy densities of 8,000 [3.3(0.1) kg], 16,000 [3.4(0.3) kg] and 32,000 [3.6(0.2) kg] mJ/cm^2. No significant differences could be detected between the three last groups.

The results of %CM before and after loading are shown in Table 3. Paired *t* test showed that there was a significant effect of mechanical loading on marginal adaptation.

Table 2 Results of linear displacement and polymerization shrinkage force for each group after 180 s of light curing

Groups (mJ/cm^2)	Linear displacement (μm)	Polymerization. shrinkage force (kg)
32,000	29.2 (0.8) a	3.6 (0.2) a
16,000	27.8 (1.1) b	3.4 (0.3) a
8,000	26.7 (1.1) c	3.3 (0.1) a
4,000	23.5 (0.7) d	2.9 (0.2) b

Levels connected by different letters are significantly different at the 0.05 level and apply to each column

Table 3 Results of percentages of continuous margins (%CM) before and after loading

Groups (mJ/cm^2)	%CM before loading	%CM after loading	Statistical difference
32,000	85.6 (10.4)	75.4 (11.5)	a
16,000	89.9 (4.3)	77.3 (9)	a
8,000	82.9 (10.4)	69.2 (12.2)	a
4,000	69.1 (12.1)	46.4 (23.5)	b

Levels connected by different letters are significantly different at the 0.05 level and apply to each column

Before loading the results were quite homogeneous. The lowest results after loading were observed in the group light cured with an energy density of 4,000 mJ/cm^2 [%CM 46.4(23.5)], that is, the one in which composite resin was light cured for 5 s. This was also the group that presented the highest SD. Above the threshold of 8,000 mJ/cm^2, no significant differences in %CM were observed between the groups.

Discussion

In the present study shrinkage stresses increased with higher energy densities, in agreement with previous studies [17]. An energy density of 8,000 mJ was the minimum required to ensure a stress-resistant adhesive interface in class V restorations of 2 mm depth. Above this threshold, no significant differences were detected between the groups, or, said differently; marginal integrity attained similar scores independently of energy of 8,000, 16,000 or 32,000 mJ used for light polymerization. This finding might be explained by the fact that by regulating the time of exposure, the same number of photons should be available for absorption by camphoroquinone molecules, which will react with the amine and form free radicals for polymerization. This has an important impact on clinical practice, because it means that above a certain level of energy, which in this study was of 8,000 mJ, the degree of

cure, in cavity depths of 2 mm, will mostly depend on the appropriate combination of light intensity and irradiation time, as exposed by Feng et al. [18]. As the material is light cured for a longer time, an increase in double bond conversion will enhance the cross-linking density and therefore, mechanical properties [19, 20]. Therefore, the first research hypothesis that light curing with different energy would affect the quality of marginal adaptation before and after fatigue conditions was validated.

It has been previously reported that a composite resin with an inferior degree of cure is rather beneficial because this may lead to a decrease in polymerization shrinkage and contraction stress [21]. The mechanism behind this phenomenon has been explained by the fact that with a very high reaction rate, polymerization becomes diffusion limited at an earlier stage in conversion [22]. Our results could show that with the highest energy density, linear displacement and polymerization force rates attained their maximum values, validating also the second research hypothesis. However, no negative effect was observed on marginal adaptation after the fatigue test. Possibly, light curing the composite resin with the highest energy density resulted in a composite restoration with adequate mechanical properties; functional forces during fatigue could be dissipated to the tooth via a stress-resistant adhesive interface. This might explain why curing the composite with the highest energy density did not affect marginal integrity after fatigue.

Based on preliminary work performed in our laboratory, the fatigue load induced in this study corresponded approximately to 2 years of clinical service. In terms of marginal adaptation, it was expected that when using a low energy density (4,000 mJ/cm^2), a low degree of conversion would take place, reducing the absolute amount of shrinkage and thus having a positive effect on marginal adaptation before stressing. However, this was not the case as already before stressing, the %CM were the lowest. We speculate that because there was not enough cross-linking, the resulted material was most probably less resistant mechanically and it is highly probably that margin degradation occurred already in the stage of marginal polishing before loading.

Finally, it should be considered that restoration depth was of 2 mm. While no significant differences at the marginal level were observed above the threshold of 8,000 mJ/cm^2, intermediate levels of energy density might be less tolerant to any variation in cavity depth, in light angulation or to any loss in power density [21]. To minimise the risk of under-curing, it might be recommended to use the highest energy density. It is worth to note that the minimum threshold of radiant exposure might be specific for each composite brand, as the shade, translucency, filler particle size, load and distribution, viscosity and resin matrix composition may dictate other values of radiant exposures, like the 10,000 and 12,000 mJ/cm^2 mentioned in recent studies [7]. Therefore, our findings apply to Tetric composite resin with the specific shade used in this experiment.

The clinical implications of the present findings might be important for both clinicians and manufacturers. Instead of recommending a minimum amount of light intensity (mW/cm^2), manufacturers of resin composites should provide with information on the amount of energy density necessary to ensure a proper polymerization for a certain restoration depth. This would be beneficial for the clinician because if the amount of light intensity delivered by the curing device is known, compensation with irradiation time can be made to attain the dose of energy necessary for polymerisation.

Conclusion

Based on the results of this study, it can be concluded that light curing with an energy density of 4,000 mJ/cm^2 generated the lowest shrinkage force and linear displacement but led to the worst marginal adaptation probably due to a poor cure. Curing the composite with an energy density of 8,000, 16,000 and 32,000 mJ/cm^2 (800 mW/cm^2 for 10, 20 or 40 s) led to progressively higher scores of linear shrinkage, but similar results of shrinkage force and marginal adaptation.

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Conflict of interest The authors declare that they have no conflict of interest.

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