Reduced Irradiation Time in Slow-curing of Resin Composite Using an Intensity-changeable Light Source

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Possibility to shorten the total irradiation time in slow-curing with an intensity-changeable light source, Curetron 7 (CT-7), was investigated for four hybrid-type resin composites. Irradiation condition with CT-7 was assigned as 10 or 20 seconds at low light intensity (230 mW/cm²) and followed by 20 or 10 seconds at high intensity (600 mW/cm²) respectively (*i.e.*, a total of 30 seconds). For a reference, irradiation was carried out for 30 seconds using a halogen lamp (900 mW/cm²). After irradiation, mechanical properties of the cured composites – in terms of microhardness and flexural strength – were evaluated. Also, cavity adaptation was examined in standardized, cylindrical dentin cavities treated with an adhesive system. Compared to the reference irradiation, slow-curing with CT-7 produced acceptable mechanical properties and better adaptation. These results suggested that total exposure time of slow-curing with CT-7 could be shortened to 30 seconds.

Key words : Resin composite, Slow-curing, Polymerization

INTRODUCTION

General practitioners place a special emphasis on shortening treatment time. Curing time for resin composites is no exception, and several light curing units (LCUs) have been developed for this purpose. Currently, several types of LCU are available: conventional quartz-tungsten-halogen lamp (QTH), plasma-arc curing unit (PAC), light amplification by stimulated emission of radiation (LASER), and light-emitting diode (LED)¹⁾. Each LCU has different intensity, spectral output, and curing mode.

Polymerization shrinkage of resin composites, which occurs during irradiation, often causes unpleasant post-operation symptoms^{2,3)}. Against this background, various attempts have been made to lessen contraction stress, *e.g.*, sandwich technique, incremental filling technique, and usage of flowable resin composite^{3–7)}. Curing mode also has an effect on contraction stress reduction, and one of the effective methods is the so-called slow-curing technique. A lot of studies have shown that this technique reduces gap formation and produces good mechanical properties (or degree of conversion) in cured resin composites^{8–17)}.

Uno *et al.*¹⁴⁾ devised a QTH LCU for slow-curing, Curetron 7 (CT-7; Osada Electric Industry, Tokyo, Japan). CT-7 is a hand-piece type light source (a light window of 10 mm in diameter) connected to the dental chair. The output spectrum of CT-7 has a sharp and single peak around 480 nm, and light intensity is changeable from the lowest 230 mW/cm² to the highest 600 mW/cm². Their study proved the

efficacy of slow-curing method when an interval was inserted between two irradiation conditions of low intensity and high intensity. However, total curing time was 50 seconds – longer than the time that practitioners expect. A shorter irradiation time will better enable the light guide to be maintained at the best curing position during light irradiation.

Therefore, the purpose of this study was to confirm if irradiation time in slow-curing could be shortened using CT-7. The hypothesis was that a total irradiation time of 30 seconds would be good enough to produce good cavity adaptation and acceptable mechanical properties in cured composites.

MATERIALS AND METHODS

Four hybrid-type resin composites and a self-etching priming system were used in this study (Table 1). Two curing light sources were used under four selected irradiation conditions (Table 2). The light intensity of each condition was monitored with a radiometer (Curing Radiometer Model 100; Demetron Kerr, Danbury, CT, USA) during the experiment.

Surface microhardness

Resin composite (Table 1) was filled into a cylindrical acrylic mold (3 mm in diameter × 2 mm in height) as a bulk. Having covered both sides with transparent strips and compressed with glass plates by hands, the composite was light-cured from one side with three different irradiation conditions: OP30, L20-H10, and L10-H20 (Table 2). Immediately after irradiation, the specimen was placed on the stage of

Table 1 Materials used in this study

Material	Code	Batch number	Composition	Manufacturer
Elitefil	AE	000009477	barium glass/silanated silica 75wt%; size 0.7 μ m, resin: Bis-GMA, UDMA, TEGDMA	Bisco, Schaumburg, IL, USA
Clearfil AP-X	APX	0630AA	barium glass, silanated colloidal silica, silanated silica, resin: Bis-GMA, TEGDMA	Kuraray Medical, Tokyo, Japan
Z100	Z100	20010927	zirconia/silica 66vol%; size range 0.01-3.5 μ m, resin: Bis-GMA, TEGDMA	3M-ESPE, St. Paul, MN, USA
Z250	Z250	20011113	zirconia/silica 66vol%; size range 0.01-3.5 μ m, resin: Bis-GMA, UDMA, Bis-EMA	
Clearfil SE Bond	SE	00295A 00364A	MDP, HEMA, multifunctional methacrylate MDP, HEMA, multifunctional methacrylate, microfiller	Kuraray Medical, Tokyo, Japan

Bis-GMA: bisphenol-glycidyl dimethacrylate;

UDMA: urethane dimethacrylate;

TEGDMA: triethylene glycol dimethacrylate;

Bis-EMA: bisphenol-polyethylene glycol diether dimethacrylate;

MDP: 10-methacryloyloxydecyl dihydrogen phosphate;

HEMA: 2-hydroxyethyl methacrylate.

Table 2 Light sources and irradiation conditions

Light source	Code	Irradiation condition	Manufacturer
Optilux 401	OP30	900 mW/cm ² × 30 sec	Demetron Kerr, Danbury, CA, USA
Curetron 7	L20-H10	230 mW/cm ² × 20 sec + 600 mW/cm ² × 10 sec	Osada Electric Industry, Tokyo, Japan
	L10-H20	230 mW/cm ² × 10 sec + 600 mW/cm ² × 20 sec	
	L20-10-H20	230 mW/cm ² × 20 sec + 10 sec (interval) + 600 mW/cm ² × 20 sec	

a microhardness indentation tester (MZT-4; Akashi, Tokyo, Japan) to measure microhardness at both top and bottom surfaces (Fig. 1). The indentation technique employed in this study used a cone-shaped indenter (68°), and hardness was calculated from the following formula: $HUT [68] = K \times \text{main load} / (\text{indentation depth})^2$, where K is a coefficient. Indentations were carried out under a preload at 0.0002 N and main load at 0.01 N for 30 seconds, first at the bottom surface and then at the top surface. Six specimens were prepared for each irradiation condi-

tion/composite combination, and indentation was carried out at five random points on each surface. All measurements were done within five minutes for each specimen. Finally, mean value and standard deviation were calculated for each material.

Flexural strength

Resin composite was filled into an acrylic mold (2.5 mm in thickness × 5.5 mm in width × 18.0 mm in length). Having covered both sides with transparent strips, the composite was compressed with glass plates by hands. Light irradiation was carried out three times on each side: first at the center and then at 1/3 from each end of the specimen. Four irradiation conditions — OP30, L20-H10, L10-H20, and L20-10-H20 (Table 2) — were conducted. The condition of L20-10-H20 was tested for a reference since Uno *et al.*¹⁴⁾ reported on good curing performance with this condition. After each condition, the irradiated specimen was gently removed from the mold and stored at 37°C for 24 hours. Then, the specimen was polished with #1000 SiC paper. Following which, three-point bending test was performed to measure flexural strength at a cross-head speed of 1.0 mm/min in a universal testing machine (Instron Model 8500; High Wycombe, UK) (Fig. 2). Six specimens were prepared for each irradiation condition/composite combination, and the mean value and standard

Fig. 1 Schematic diagram of microhardness measurement. Each specimen was measured at ① bottom surface and ② top surface, immediately after irradiation. Measurements were carried out at five points on each surface. Indentation method (AKASHI MZT-4, Tokyo, Japan).

Fig. 2 Schematic diagram of flexural strength measurement. All specimens were measured after storage at 37°C for 24 hours. Three-point bending test (INSTRON Model 8500).

deviation were calculated for each material.

Cavity adaptation

Extracted human molars stored in 0.5 w/w% chloramine-T solution were used in this study. Buccal surface of the tooth was ground with #600 SiC paper under running water until a flat dentin surface was exposed, and a cylindrical dentine cavity (3.0 mm in diameter $\times$ 1.5 mm in depth) was prepared thereby. The cavity was treated with a self-etching priming adhesive system according to manufacturer's instructions, and filled with one of the four resin composites as a bulk (Table 1). After being covered with transparent strips, the resin composite was light-cured under one of the four different irradiation conditions: OP30, L20-H10, L10-H20, or L20-10-H20 (Table 2). The condition of L20-10-H20 was also tested, as described for flexural strength measurement. Excess material was immediately removed by gently wet grinding with #1000 to #1500 SiC paper until the margin was exposed. After marginal adaptation was evaluated under an incident microscope (BX60M; Olympus, Tokyo, Japan) at $\times 500$ magnification, the tooth was embedded in epoxy resin. The specimen was longitudinally sectioned with a low-speed saw (Isomet; Buehler, IL, USA) at the center of the restoration. Wall adaptation was evaluated at seven points on each surface of the sec-

Fig. 3 Evaluation of cavity adaptation. Observation points were: ① top surface; ② outer 1/3; ③ inner 1/3; ④ line angle; and ⑤ cavity floor.

tion — outer 1/3, inner 1/3, line angle, and cavity floor — under the incident microscope (Fig. 3). If a gap was found between the cavity wall and composite, the maximum gap width would be recorded at each observation point. Six specimens were prepared for each irradiation condition/composite combination.

Statistical analyses

Microhardness was analyzed with three- and two-way ANOVA and Scheffe's test at 5% level of significance. Flexural strength of resin composite surfaces was examined with two-way ANOVA and Scheffe's test. Cavity adaptation was assessed using Kruskal-Wallis and Mann-Whitney U-test at 5% level of significance.

RESULTS

Surface microhardness

Microhardness results for each irradiation condition were given in Table 3. Three-way ANOVA — which analyzed the effects of irradiation condition, material, and measured surface on microhardness — revealed the interaction between surface and material ($p < 0.05$). For each material, two-way ANOVA showed no interactions between irradiation condition and measured surface ($p > 0.05$). In Table 4-1, it was found that irradiation condition had no influence on microhardness. In Table 4-2, it was shown that measured surface had a significant effect on microhardness. When comparing microhardness between top and bottom surfaces, the following irradiation condition/composite combinations showed no significant differences: OP30 for all materials; L10-H20 for Z100; and L20-H10 and L10-H20 for APX (Scheffe, $p > 0.05$). In other groups, the top surface was harder than the bottom one ($p < 0.05$).

Flexural strength

Flexural strength results for each irradiation condi-

Table 3 Microhardness (HUT/68) of cured composite surfaces

Condition	Composite	Top surface	Bottom surface
OP30	AE	26 (4.4)	22 (6.7)
	APX	34 (7.0)	32 (4.7)
	Z100	32 (2.9)	29 (3.8)
	Z250	27 (3.9)	26 (4.2)
L20-H10	AE	23 (2.6)	16 (2.7)
	APX	35 (5.0)	33 (3.3)
	Z100	31 (2.3)	29 (3.1)
	Z250	30 (3.5)	24 (2.6)
L10-H20	AE	23 (2.1)	17 (2.4)
	APX	33 (7.0)	30 (4.7)
	Z100	28 (4.1)	28 (3.7)
	Z250	28 (3.4)	24 (4.1)

Mean (S.D.) is given ($n=5$).

Table 4-1 Comparison of microhardness (HUT/68) among irradiation conditions for each material

Composite	OP30	L20-H10	L10-H20
AE			
APX			
Z100			
Z250			
Horizontal line denotes no significant differences (p=0.05).			

Table 4-2 Comparison of microhardness (HUT/68) among between top and bottom surfaces for each material

Composite	OP30	L20-H10	L10-H20
AE	—	○	○
APX	—	—	—
Z100	—	○	—
Z250	—	○	○

○: significant difference;

—: not significant difference (p=0.05).

tion are given in Table 5. Two-way ANOVA revealed independent influence of both irradiation condition and material. The strength of Ælitefil was significantly lower than those of the other three materials in all conditions (Scheffe, $p < 0.05$). When comparing irradiation conditions, L20-H10 and L10-H20 produced equal strength as OP30 for all materials (Scheffe, $p > 0.05$) (Table 6). Furthermore, L10-H20 and L20-10-H20 showed higher strength than L20-H10 ($p > 0.05$).

Cavity adaptation

Table 7 shows the respective gap formation measurements for each irradiation condition/material group.

Table 7 Cavity adaptation

Condition	Composite	top surface	outer 1/3	inner 1/3	line angle	cavity floor
OP30	AE	0, 0, 0, 2, 4, 4	0, 0, 0, 0, 0, 0	0, 0, 0, 1, 1, 10	0, 0, 1, 3, 8, 12	0, 8, 8, 10, 14, 18
	APX	0, 0, 0, 1, 2, 2	0, 0, 0, 0, 0, 0	0, 0, 0, 0, 0, 1	0, 0, 0, 0, 0, 0	0, 0, 1, 2, 4, 6
	Z100	0, 1, 1, 2, 6, 7	0, 0, 0, 0, 1, 5	0, 0, 0, 1, 2, 4	0, 0, 0, 0, 1, 2	0, 0, 0, 0, 0, 1
	Z250	0, 0, 0, 0, 0, 1	0, 0, 0, 0, 0, 0	0, 0, 0, 0, 0, 2	0, 0, 0, 1, 1, 2	0, 0, 0, 0, 1, 1
L20-H10	AE	0, 0, 2, 2, 3, 4	0, 0, 0, 0, 0, 2	0, 0, 0, 0, 10, 12	0, 0, 0, 0, 10, 10	0, 0, 2, 6, 10, 10
	APX	0, 0, 0, 0, 0, 0	0, 0, 0, 0, 0, 0	0, 0, 0, 0, 0, 10	0, 0, 0, 0, 1, 4	0, 0, 0, 4, 4, 14
	Z100	0, 0, 0, 0, 4, 6	0, 0, 0, 0, 4, 6	0, 0, 0, 4, 4, 6	0, 0, 0, 0, 2, 2	0, 0, 2, 2, 3, 4
	Z250	0, 0, 0, 0, 0, 1	0, 0, 0, 0, 0, 1	0, 0, 0, 0, 0, 0	0, 0, 0, 0, 0, 1	0, 0, 0, 0, 0, 0
L10-H20	AE	0, 0, 0, 1, 1, 3	0, 0, 0, 0, 0, 0	0, 0, 0, 0, 0, 4	0, 0, 0, 0, 0, 3	0, 0, 0, 0, 0, 2
	APX	0, 0, 0, 0, 0, 0	0, 0, 0, 0, 0, 0	0, 0, 0, 0, 2, 3	0, 0, 0, 0, 1, 4	0, 0, 0, 0, 0, 2
	Z100	0, 0, 0, 0, 0, 4	0, 0, 0, 0, 0, 4	0, 0, 0, 0, 4, 8	0, 0, 0, 0, 1, 6	0, 2, 2, 3, 3, 11
	Z250	0, 0, 0, 0, 0, 0	0, 0, 0, 0, 0, 0	0, 0, 0, 0, 0, 0	0, 0, 0, 0, 0, 1	0, 0, 0, 0, 0, 0
L20-10-H20	AE	0, 0, 0, 0, 0, 0	0, 0, 0, 0, 0, 0	0, 0, 0, 0, 0, 0	0, 0, 0, 0, 0, 1	0, 0, 0, 0, 0, 3
	APX	0, 0, 0, 0, 0, 0	0, 0, 0, 0, 0, 0	0, 0, 0, 0, 0, 0	0, 0, 0, 0, 1, 2	0, 0, 0, 0, 0, 0
	Z100	0, 0, 0, 0, 2, 2	0, 0, 0, 0, 0, 3	0, 0, 0, 0, 3, 4	0, 0, 1, 1, 2, 3	0, 0, 0, 0, 1, 3
	Z250	0, 0, 0, 0, 2, 2	0, 0, 0, 0, 0, 3	0, 0, 0, 0, 3, 4	0, 0, 1, 1, 2, 3	0, 0, 0, 0, 1, 3

Maximum gap width (μm) at the measurement points (n=6).

Table 5 Flexural strength of cured composites

Condition	Composite	MPa
OP30	AE	178 (5.0)
	APX	205 (25)
	Z100	197 (21)
	Z250	203 (16)
L20-H10	AE	147 (11)
	APX	184 (17)
	Z100	195 (6.2)
	Z250	206 (27)
L10-H20	AE	168 (8.3)
	APX	209 (21)
	Z100	194 (12)
	Z250	230 (7.0)
L20-10-H20	AE	157 (24)
	APX	211 (17)
	Z100	185 (26)
	Z250	237 (7.4)

Mean (S.D.) is given (n=5).

Table 6 Comparison of flexural strength among the irradiation conditions

L20-H10		
OP30		
L20-10-H20		*
L10-H20		

Vertical lines denote no significant differences ($p > 0.05$).Asterisk denotes a difference between irradiation conditions connected ($p < 0.05$).

Table 8 Comparison of cavity adaptation among the irradiation conditions

Elitefil cavity	OP30								
	L20-H10								
	L10-H20								
	L20-10-H20								
Z100 cavity	OP30								
	L20-H10								
	L10-H20								
	L20-10-H20								

Vertical lines denote no significant differences ($p > 0.05$).

Asterisk denotes a difference between irradiation conditions connected ($p < 0.05$).

For each group, adaptation differed significantly at top surface and cavity floor among the measurement points (Kruskal-Wallis, $p < 0.05$). Moreover for Elitefil and Z100, there were significant differences among the irradiation conditions (Mann-Whitney, $p < 0.05$). L10-H20 and L20-10-H20 for Elitefil and L10-H20 for Z100 showed significantly better adaptation than OP30 ($p > 0.05$) (Table 8).

DISCUSSION

Polymerization shrinkage is a major drawback of resin composite restorations. When a composite is bonded to the cavity wall, polymerization shrinkage generates a stress at the bonding interface according to its quantification (volumetric and linear shrinkage), phase (pre-gel, post-gel, and total shrinkage), and distribution (uniform and non-uniform shrinkage)⁶⁾. Shrinkage stress is a property-complex, which means it is affected by multiple material properties (polymerization contraction and modulus development), geometry, and boundary conditions⁶⁾. Indeed, a lot of studies showed that contraction stress was associated with elastic modulus and degree of conversion of the composite, and also with cavity adaptation^{17–26)}. Sakaguchi *et al.*²⁷⁾ found that polymerization contraction force rate was linearly correlated to irradiance. In this vein, it is very important to perform slow-curing with a low light intensity at the pre-gel stage of the composite to reduce contraction stress¹¹⁾. An argument against this slow-curing approach is that low light intensity likely results in poor conversion of the composite. One solution is the two-step curing method. Composites irradiated with higher light intensity followed by low intensity have shown good mechanical properties and better cavity adaptation^{8,9,13,14,23)}. However, in clinical situations, a shorter irradiation time is more desirable for both clinician and patient.

This study sought to verify whether total expo-

sure time could be shortened to 30 seconds. In terms of microhardness, there were no significant differences among the three irradiation conditions: OP30, L20-H10, and L10-H20. In terms of flexural strength, no differences were found between L20-H10 and OP30, and among OP30, L20-10-H20, and L10-H20. These results implied that L20-H10 and L10-H20, though only of 30 seconds' total exposure time, produced favorable mechanical properties. Regarding cavity adaptation in Elitefil and Z100, L20-10-H20 produced the best adaptation among the conditions tested. This concurred with the result of Uno *et al.*¹⁴⁾. Further, compatible good adaptation was generated by L10-H20 rather than L20-H10 for these two composites.

Energy density (J/cm^2) is expressed as a value: power density (W/cm^2) $\times$ exposure time (seconds)²⁸⁾. Vandewalle *et al.*²⁹⁾ showed that energy density and degree of conversion had significant influence on gingival marginal defects, but not on microleakage. Of interest is that total energy densities of L20-H10 and L10-H20 were $10.6 \text{ J}/\text{cm}^2$ and $14.3 \text{ J}/\text{cm}^2$ respectively, which were lower than OP30 ($27.0 \text{ J}/\text{cm}^2$) and L20-10-H20 ($16.6 \text{ J}/\text{cm}^2$). In particular, reduced energy density seemed to be advantageous for cavity adaptation. In this study, we did not measure degree of conversion. However, considering the results of microhardness and flexural strength, the two irradiation conditions with lower energy density enabled the composites to be properly polymerized. Hofmann *et al.*¹⁵⁾ demonstrated that soft-start halogen irradiation protocols succeeded in reducing the speed of contraction while maintaining an acceptable degree of cure.

For Elitefil and Z250 in this study, hardness at the bottom surface of 2-mm thick specimen was lower than that at the top surface, when the condition of L20-H10 or L10-H20 was conducted. Tanaka *et al.*³⁰⁾ measured the light intensity transmitted through cured resin composites, and reported that Elitefil transmitted light poorly as compared to other commercialized hybrid-type composites. When composite is of a certain thickness, mechanical properties at the bottom of the bulk may be related to the light intensity transmitted. In other words, the contents of monomers and fillers — as well as shades — are crucial factors that determine the polymerization of composites. Z250 is similar in composition to Z100, except for monomer Bis-EMA. But, it is not clear if the difference in microhardness between Z250 and Z100 could be attributed to Bis-EMA. Nevertheless, each material might have an optimal irradiation condition required for better curing performance of the composite^{15,31)}.

CT-7 has a narrow output spectrum, which is very close to LED LCU. The narrow band with a peak LED emission correctly activates camphorquinone (absorption maximum at 468 nm), leading to free radical polymerization reaction. How-

ever, for other photoinitiators in a resin composite, the so-called co-initiators have different absorption ranges (absorption maximum at 410 nm), and thus LED emission may fail to activate them for polymerization^{32,33}. Therefore, a careful selection of resin composite is emphatically necessary when a LED is used as the light source³³⁻³⁵. In general, compatibility between light spectrum and photoinitiation system should be considered not only for LED, but also for other LCUs.

Our hypothesis that total irradiation time of 30 seconds might be good enough to produce good cavity adaptation and acceptable mechanical properties in cured composites was totally confirmed. In particular, the condition of L10-H20 generated equivalent mechanical properties as OP30, and even better cavity adaptation than OP30. However, flexural strength and cavity adaptation were partially affected by the characteristics of the materials used. In conclusion, it was possible to reduce exposure time when CT-7 was used for slow-curing of resin composite restorations.

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REFERENCES

- Burgess JO, Walker RS, Porche CJ, Rappold AJ. Light curing — An update. *Compend Contin Educ Dent* 2002; 23: 889-906.
- Bausch RJ. Clinical significance of polymerization shrinkage of composite resin. *J Prosthet Dent* 1982; 48: 59-67.
- Davidson CL, Feilzer AJ. Polymerization shrinkage and polymerization shrinkage stress in polymer based restoratives. *J Dent* 1997; 25: 435-440.
- Uno S, Shimokobe H. Contraction stress and marginal adaptation of composite restorations in dentinal cavity. *Dent Mater J* 1994; 13: 19-24.
- Bowen RL, Marjenhoff WA. Dental composites/glass ionomers: The materials. *Adv Dent Res* 1992; 6: 44-49.
- Versluis A, Tantbirojn D. Theoretical considerations of contraction stress. *Compend Contin Educ Dent* 1999; 20(Suppl): 24-32.
- Kugel G, Perry R. Direct composite resins: An update. *Compend Contin Educ Dent* 2002; 23: 593-606.
- Uno S, Asmussen E. Marginal adaptation of a restorative resin polymerized at reduced rate. *Scand J Dent Res* 1991; 99: 440-444.
- Mehl A, Hickel R, Kunzelmann KH. Physical properties and gap formation of light-cured composites with and without 'soft-start-polymerization'. *J Dent* 1997; 25: 321-330.
- Kanka III J, Suh BI. Pulse activation: reducing resin-based composite contraction stresses at the enamel cavosurface margins. *Am J Dent* 1999; 12: 107-112.
- Watts DC, Al Hindi A. Intrinsic 'soft-start' polymerization shrinkage-kinetics in an acrylate-based resin-composite. *Dent Mater* 1999; 15: 39-45.
- Sahafi A, Peutzfeldt A, Asmussen E. Soft-start polymerization and marginal gap formation *in vitro*. *Am J Dent* 2001; 14: 145-147.
- Yoshikawa T, Burrow MF, Tagami J. A light curing method for improving marginal sealing and cavity wall adaptation of resin composite restorations. *Dent Mater* 2001; 17: 359-366.
- Uno S, Tanaka T, Natsuizaka A, Abo T. Effect of slow-curing on cavity wall adaptation using a new intensity-changeable light source. *Dent Mater* 2003; 19: 147-152.
- Hofmann N, Denner W, Hugo B, Klaiber B. The influence of plasma arc vs. halogen standard or soft-start irradiation on polymerization shrinkage kinetics of polymer matrix composites. *J Dent* 2003; 31: 383-393.
- Rahiotis C, Kakaboura A, Loukidis M, Vougiouklakis G. Curing efficiency of various types of light-curing units. *Eur J Oral Sci* 2004; 112: 89-94.
- Bayindir YZ, Yildiz M, Bayindir F. The effect of 'soft-start polymerization' on surface hardness of two packable composites. *Dent Mater J* 2003; 22: 610-616.
- Braem M, Lambrechts P, Vanherle G, Davidson CL. Stiffness increase during the setting of dental composite resins. *J Dent Res* 1987; 66: 1713-1716.
- Emami N, Söderholm KJM, Berglund LA. Effect of light power density variations on bulk curing properties of dental composites. *J Dent* 2003; 31: 189-196.
- Asmussen E, Peutzfeldt A. Two-step curing: influence on conversion and softening of a dental polymer. *Dent Mater* 2003; 19: 466-470.
- Chen HY, Manhart J, Hickel R, Kunzelmann KH. Polymerization contraction stress in light-cured packable composite resins. *Dent Mater* 2001; 17: 253-259.
- Braga RR, Ferracane JL. Contraction stress related to degree of conversion and reaction kinetics. *J Dent Res* 2002; 81: 114-118.
- Lim BS, Ferracane JL, Sakaguchi RL, Condon JR. Reduction of polymerization contraction stress for dental composites by two-step light-activation. *Dent Mater* 2002; 18: 436-444.
- Yoshikawa T, Burrow MF, Tagami J. The effects of bonding system and light curing method on reducing stress of different C-factor cavities. *J Adhes Dent* 2001; 3: 177-183.
- Luo Y, Lo ECM, Wei SHY, Tay FR. Comparison of pulse activation vs. conventional light-curing on marginal adaptation of a compomer conditioned using a total-etch or a self-etch technique. *Dent Mater* 2002; 18: 36-48.
- Cho BH, Dickens SH, Bae JH, Chang CG, Son HH, Um CM. Effect of interfacial bond quality on the direction of polymerization shrinkage flow in resin composite restorations. *Oper Dent* 2002; 27: 297-304.
- Sakaguchi RL, Wiltbank BD, Murchison CF.

- Contraction force rate of polymer composites is linearly correlated with irradiance. *Dent Mater* 2004; 20: 402-407.
- 28) Suh BI. Controlling and understanding the polymerization shrinkage-induced stresses in light-cured composites. *Compend Contin Educ Dent* 1999; 20(Suppl): 34-41.
- 29) Vandewalle KS, Ferracane JL, Hilton TJ, Erickson RL, Sakaguchi RL. Effect of energy density on properties and marginal integrity of posterior resin composite restorations. *Dent Mater* 2004; 20: 96-106.
- 30) Tanaka T, Uno S, Ikeda T, Ominato R, Sano H. Intensity of the light transmitted through resin composites at irradiation with a variable-intensity light source. *Hokkaido J Dent Sci* 2000; 21: 110-117.
- 31) Suh BI, Cripe CA, Yin R. Light intensity and exposure time effects on light-cured composites. *J Dent Res* 1998; 77: 641, Abstr No. 73.
- 32) Park YJ, Chae KH, Rawls HR. Development of a new photoinitiation system for dental light-cure composite resins. *Dent Mater* 1999; 15: 120-127.
- 33) Uhl A, Sigusch BW, Jandt KD. Second generation LEDs for polymerization of oral biomaterials. *Dent Mater* 2004; 20: 80-87.
- 34) Hofmann N, Hugo B, Klaiber B. Effect of irradiation type (LED or QTH) on photo-activated composite shrinkage strain kinetics, temperature rise, and hardness. *Eur J Oral Sci* 2002; 110: 471-479.
- 35) Asmussen E, Peutzfeldt A. Light-emitting diode curing: Influence on selected properties of resin composites. *Quintessence Int* 2003; 34: 71-75.