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Laboratory Research

The Linear Shrinkage and Microhardness of Packable Composites Polymerized by QTH or PAC Unit

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Clinical Relevance

When packable composites are cured using the PAC system, 12 seconds of light curing is recommended for shallow cavities that do not exceed 2 mm, and many measures should be applied in order to avoid the clinical complications associated with a rapid cure.

SUMMARY

This study evaluated the effectiveness of a plasma arc curing (PAC) unit for packable resin composite curing. The amount and speed of polymerization shrinkage and the microhardness of packable composites were evaluated in order to compare the PAC unit's effectiveness with a quartz tungsten halogen (QTH) unit. Sure Fil (Dentsply Caulk), Pyramid (BISCO Inc) and Synergy Compact (Colténe/Whaledent) were used as the packable composites. In the case of curing with the PAC unit, the composites were light cured with Apollo 95E (DMD System Inc) for 1 second (Group 1), 2 seconds (Group 2), 3 seconds (Group 3), 6 seconds (Group 4) and 12 seconds (Group 5). For light curing with the QTH unit, the composites were light cured for 60 seconds using XL3000 (Group 6). The linear polymerization shrinkage of each composite was measured using a custom made linometer, and the data was stored in a computer every 0.5 to 0.55 seconds for a total of 60 seconds. For each composite, the amount of polymerization was compared using one-way ANOVA with Tukey at the 95% confidence level. In order to compare the speed of polymerization, the peak time (PT), showing the highest speed of polymerization and maximum speed of polymerization (S_{max}), were determined from the data and compared using one-way ANOVA with Tukey at the 95% confidence level for each material.

Based on the statistical analysis among the PAC-cure groups (Groups 1 through 5), the group that was not statistically different from the QTH-cure group (Group 6) in the amount of linear polymerization shrinkage was determined for each material, and the corresponding curing time of the group was defined as the tentative minimum PAC-curing time (TMPT).

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For microhardness measurements, the samples were placed in a 2-mm thick Teflon plate. Twenty specimens, randomly divided into the PAC-cure group (Group 1) or the QTH-cure group (Group 2), were prepared for each material. In Group 1, each composite was light cured for TMPT with the PAC unit. In Group 2, each composite was light cured for 60 seconds with the QTH unit. Microhardness was measured on the upper and lower surface. For each material, the microhardness of the upper and lower surface of Groups 1 and 2 was analyzed using two-way ANOVA with Tukey at the 95% confidence level.

The amount of polymerization was Group 1<Group 2<Group 3<Group 4<Groups 5, 6 in the Sure Fil composite ($p<0.05$); Groups 1, 2<Group 3<Groups 4, 6<Group 5 in the Synergy Compact composite ($p<0.05$) and Group 1 <Group 2 <Group 3 <Groups 4, 6 <Group 5 in the Pyramid composite ($p<0.05$)

Regarding the speed of polymerization, the order of PT was G1, G2, G3<G4, G5<G6 ($p<0.05$). The order of R_{max} was G6<G1, G2, G3, G4, G5 in Sure Fil; G6<G1<G2, G3, G4<G5 in Synergy Compact ($p<0.05$) and G6<G1<G2, G3<G4, G5 in Pyramid ($p<0.05$)

On the upper surface, there was no statistical difference in microhardness between Groups 1 and 2 in all materials. On the lower surface, the microhardness of Group 2 was significantly higher than Group 1 in all materials. In all materials in Group 1 and the Synergy Compact of Group 2, microhardness of the upper surface was significantly higher than the lower surface ($p<0.05$). In Sure Fil and Pyramid of Group 2, there was no difference in microhardness between the upper and lower surfaces.

INTRODUCTION

Packable composites have been widely used for posterior restorations, because they are designed to provide a non-stick, packable behavior during manipulation (Leinfelder, Bayne & Swift, 1999). Some manufacturers of packable composites also recommend a bulk cure, because they provide a deeper cure, and the amount of polymerization contraction is less than a hybrid multipurpose composite. However, incremental curing techniques are still widely used, because they provide more uniform and reliable polymerization of composites (Yap, 2000). Thus, restoring posterior teeth with a composite restoration is believed to be a more time consuming and technique sensitive procedure than an amalgam restoration. A more powerful and effective polymerization procedure may help to reduce the time required for the clinical procedure.

It has been reported that the power density essential for the effective polymerization of a composite needs to be >280mW/cm^2 (Rueggeberg, Caughman & Curtis, 1994). In order to polymerize a composite effectively, light curing units with an improved power density need to be developed. Currently, the widely used quartz tungsten halogen (QTH) units have power densities ranging from 400 to 1300mW/cm^2. Recently, a new type of light curing system, the plasma arc curing (PAC) unit, has been introduced. It uses a high-frequency electrical field to generate plasma energy, and matter is thereby transformed into a mixture of ions, electrons and molecules. The significant amount of energy released during this process is used to cure photosensitive composites. The PAC unit emits light with a higher power density than the conventional QTH unit. The wavelength of light emitted from a PAC unit is approximately 470 nm; whereas, it is between 400-520 nm in a conventional QTH unit. The manufacturers assert that a PAC unit cures a composite material in one-to-three seconds and decreases the amount of polymerization shrinkage. However, Park, Krejci and Lutz (2002) reported that the recommended three-second curing time was insufficient to optimally cure composites in Z100 and Tetric Ceram. In addition, they reported that a newly developed plasma arc curing unit, Apollo 95E, did not properly cure the composite when the layer thickness exceeded 2 mm and required a longer curing time than that recommended by the manufacturer.

Using a PAC unit in packable composite curing may help to reduce the time-consuming polymerization procedure in a posterior restoration. However, it may cause a more rapid development of a polymerization contraction force. Stresses arising from polymerization shrinkage may contribute to post-operative pain, microleakage and recurrent caries (Eick & Welch, 1986); additionally, the stress in a cavity increases as the c-factor increases (Feilzer, de Gee & Davidson, 1987). Since the amount and speed of the polymerization contraction in packable composites can influence the clinical performance of a posterior restoration, basic information on these factors will provide valuable information for further research. However, little information is currently available.

This study evaluated the effectiveness of a PAC unit for packable resin composites. In order to compare its effectiveness with the QTH unit, this study compared the amount and speed of polymerization contraction in packable composites that were light cured with either the QTH or PAC system. In addition, the microhardness of 2-mm thick packable composites light cured with PAC or QTH were compared on both the upper and lower surface.

METHODS AND MATERIALS

A. Measurement of Linear Polymerization Shrinkage

Sure Fil (Dentsply Caulk, Milford, DE, USA), Pyramid (BISCO Inc, Schaumburg, IL, USA) and Synergy Compact (Colténe/ Whaledent, Altstätten, Switzerland) were used as the posterior composites (Table 1). The composites were transferred to a Teflon mold to ensure the same amount of composite for each linometer sample. The composite was then transferred to a disk in the custom-made linometer, which had been previously coated with a separating glycerin gel. The resin composite was then covered with a glass slide and loaded under constant pressure. The surface of the glass slide that faced the composite had been previously coated with a separating gel. The composites were light cured with either the QTH unit (XL 3000, 3M Dental Product, St Paul, MN, USA) or PAC unit (Apollo 95E, DMD System Inc, CA, USA). The tip of the curing light was positioned as close as possible to the slide glass (Figure 1). In the case of the light curing using the PAC unit, the composite was light cured for 1 second (Group 1), 2 seconds (Group 2), 3 seconds (Group 3), 6 seconds (Group 4) or 12 seconds (Group 5). When the composites were light cured with the PAC unit for 6 or 12 seconds, an approximately 1 second time elapse was required after 3 seconds of light activation due to the inherent properties of the light curing unit. In the case of the light curing using the QTH unit, the composite was light cured for 60 seconds with XL3000 (Group 6) with a 700 mW/cm^2 power density, as determined by a Coltolux Light Meter (Colténe, Altstätten, Switzerland). As the composite under the glass slide was cured, it shrank towards the upward direction, and the aluminum disk under the composite was moved upward as well. The amount of disk displacement caused by linear shrinkage of the resin composite was measured using an LVDT linometer (R&B Inc, Daejon, South Korea). The digital data was recorded on a computer every 0.5 to 0.55 seconds for 60 seconds. Fifteen measurements for each group were made. For each composite, the amount of linear shrinkage that occurred in 60 seconds from each group was compared by ANOVA using a Tukey's test as a post hoc test at the 95% confidence level. The thickness of the light cured samples was measured at 0.01 mm.

B. Determination of Speed of Early Polymerization Linear Shrinkage

Using the data obtained in Section A, the rate of early polymerization shrinkage from the start of curing to 15 seconds was calculated using Microsoft Excel.

The speed of polymerization at time = t was calculated as follows:

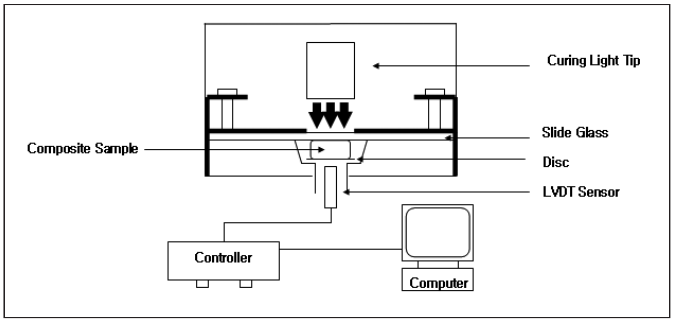

Figure 1. *Schematic diagram of linometer with a composite sample in place.*

$S_t = (L_{t+\Delta t} - L_{t-\Delta t})/(T_{t+\Delta t} - T_{t-\Delta t})$

S_t : Speed of polymerization shrinkage at time t

$L_{t+\Delta t}$: Amount of linear shrinkage at time t + Δt

$L_{t-\Delta t}$: Amount of linear shrinkage at time t - Δt

$T_{t+\Delta t}$: The time when $L_{t+\Delta t}$ was measured.

$T_{t-\Delta t}$: The time when $L_{t-\Delta t}$ was measured.

(Δt was 0.5-0.55 seconds in this study).

From this calculation, the peak time (PT), which showed the highest speed of polymerization, and the maximum speed of polymerization shrinkage (S_{max}) were determined. For each composite, PT and S_{max} were compared between groups using a one-way ANOVA with a Tukey's test as a post hoc test at the 95% confidence level.

C. Determination of Tentative Minimum PAC-curing Time (TMPT)

Based on the statistical analysis reported in Section A, among the PAC-cure groups (Groups 1-5), the group not statistically different from the QTH-cure group (Group 6) in the amount of linear polymerization shrinkage was determined for each material, and the group's corresponding curing time was defined as the tentative minimum PAC-curing time (TMPT).

D. Measurement of the Microhardness

A 6-mm diameter hole was made in a 2-mm thick Teflon plate, and a glass slide was positioned along the lower side of the hole. Titanium-coated instruments (Composite Instrument, Colténe, Switzerland) were used to place the packable composites (Table 1) into the mold. A glass slide was placed on top of the composites and pressed flat. Twenty specimens were prepared for

Table 1: *The Posterior Packable Composites Used in This Study*

Composites	Manufacturer	Lot #
Pyramid	BISCO Inc, Schaumburg, IL, USA	0100014949
Synergy Compact	Coltene/Whaledent, Altstätten, Switzerland	LH725
Sure Fil	Dentsply Caulk, Milford, DE, USA	011211

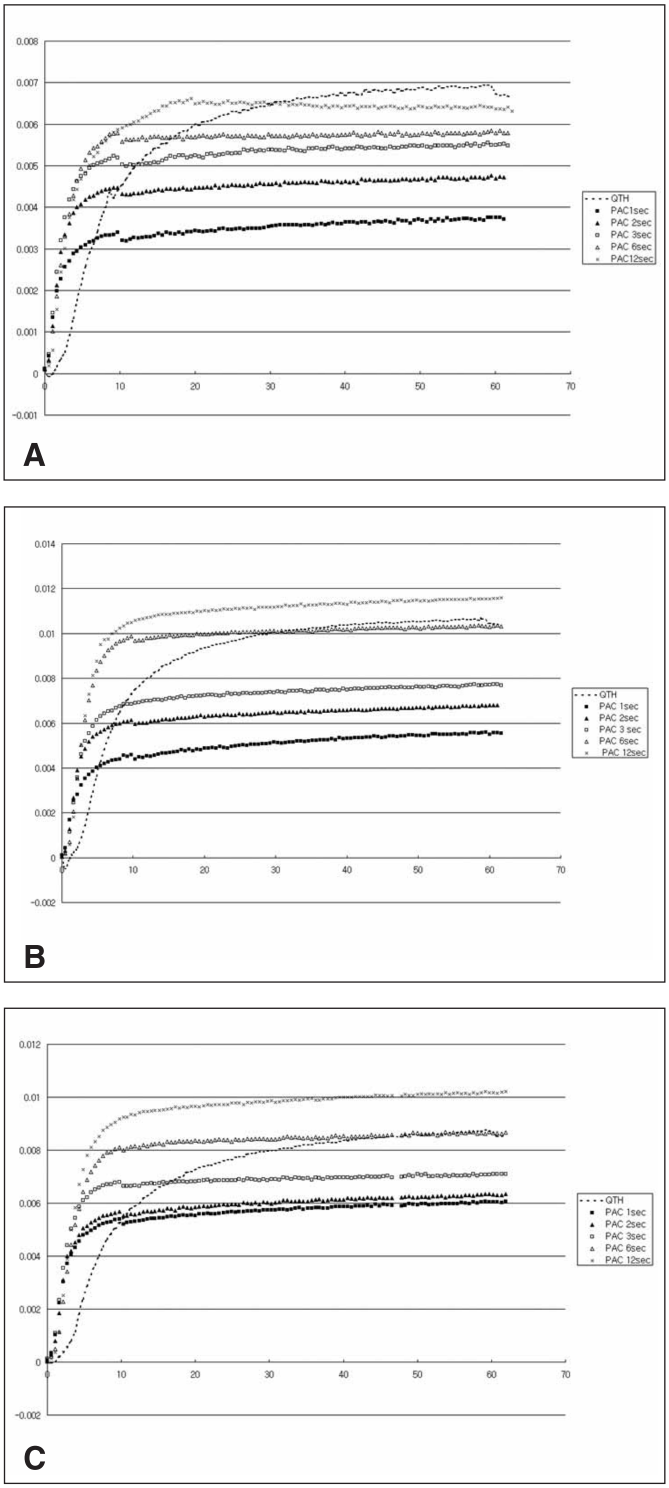

Figure 2. *Change in the amount of linear polymerization shrinkage versus time in Surefil (Figure 2a), Pyramid (Figure 2b) and SynergyCompact (Figure 2c), which were light cured with PAC or QTH.*

each material and divided randomly into two groups. The specimens were light cured with either the PAC (Group 1) or QTH unit (Group 2). For the PAC unit, each composite was light cured for TMPT. For the QTH unit, each composite was light cured for 60 seconds. After the composites were light cured with the QTH or PAC units, the specimens were removed from the mold. The upper (closer to the light source) and lower surfaces of the specimens were marked with a pen. The specimens were then stored in the dark for seven days in 100% humidity at 37°C. The microhardness of the upper and lower surfaces were then measured using a Vickers hardness-measuring instrument (Optidur, Göttfert Feinwerktechnik GmbH, Buchen, Germany). For each material, the microhardness of the upper and lower surface of Groups 1 and 2 was analyzed using a two-way ANOVA with a Tukey test at the 95% confidence level.

RESULTS

A. Measurement of the Linear Polymerization Shrinkage

The order of polymerization shrinkage in 60 seconds was Group 1< Group 2< Group 3 < Group 4 < Groups 5, 6 in the Sure Fil composite (p<0.05); Group 1 < Group 2 <Group 3 < Groups 4, 6 < Group 5 in the Pyramid composite (p<0.05) and Groups 1, 2< Group 3< Groups 4, 6< Group 5 in the Synergy Compact composite (p<0.05) (Table 2, Figure 2a,b,c).

The average thickness of the specimens was 1.30 ± 0.03 mm.

B. Determination of the Polymerization Shrinkage Speed

In all materials, the order of PT was G1, G2, G3<G4, G5<G6 (p<0.05).

The order of S_{max} was G6<G1, G2, G3, G4, G5 in Sure Fil, G6<G1<G2,G3<G4,G5 in Pyramid (p<0.05) and G6<G1<G2, G3, G4<G5 in Synergy Compact (p<0.05) (Table 3, Figure 3 a,b,c).

C. Determination of TMPT

The TMPT was 12 seconds in the Sure Fil composite and 6 seconds in the Pyramid and Synergy Compact composites (Table 2).

D. Measurement of the Microhardness

For all materials, significant differences in microhardness were observed for both curing methods (Group 1 or 2) (p<0.05) and observation surfaces (upper or lower surface) (p<0.05). A significant interaction existed between the curing methods and the observation surface for all materials (p<0.05).

In microhardness of the upper surface, there was no difference between Group 1 and 2 for all materials. However, microhardness of the lower surface in Group 2 was significantly higher than for Group 1 for all materials (p<0.05). Microhardness of the upper surface was significantly higher than the lower surface in Group 1 and Synergy Compact of Group 2; whereas, there was no difference in Sure Fil and Pyramid of Group 2 (Figure 4).

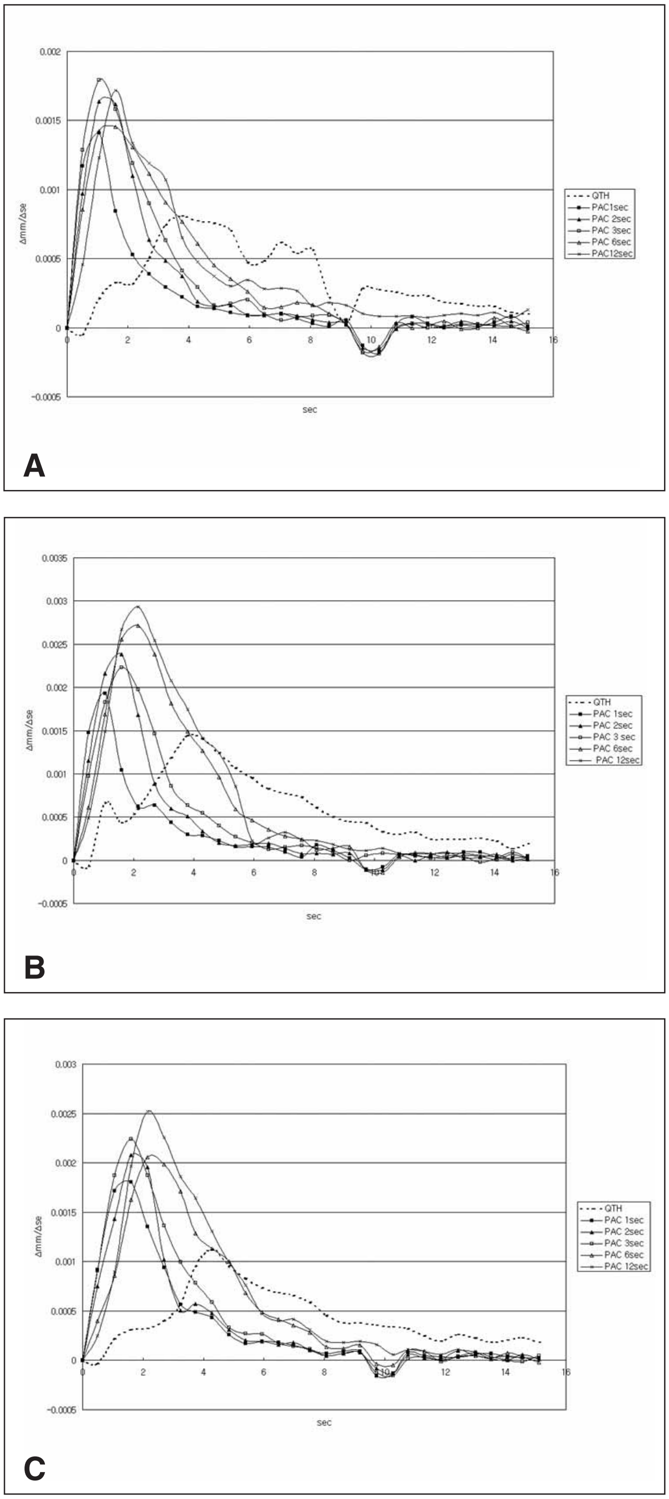

Figure 3. *Change in the speed of linear polymerization shrinkage in Sure Fil (Figure 3a), Pyramid (Figure 3b) and SynergyCompact (Figure c), which were light cured with PAC or QTH.*

DISCUSSION

Polymerization shrinkage of a resin composite can be easily and accurately measured by a specially designed linometer (de Gee, Feilzer & Davidson, 1993; Park & others, 2002).

In Synergy Compact and Pyramid, 12 seconds of PAC curing resulted in more linear shrinkage than 60 seconds of the QTH cure (Figure 2b,c). According to the manufacturer, the average power density of Apollo95E is 1370mW/cm^2. The energy density of the 12 second PAC cure was 16.44 J/cm^2 (1.37 W/cm^2 x 12 seconds); whereas, it was 42 J/cm^2 for the 60 second QTH cure (0.7 W/cm^2 x 60). The power density of the PAC and QTH systems cannot be directly compared, because the light emitted by the two units had a different spectrum. The wavelength of light emitted by the PAC unit is approximately 470 nm, which is effective in CQ activation; whereas it ranges from 400 to 520 nm in a conventional QTH unit. Considering the relatively narrower spectrum of emitted light in the PAC system, the PAC system appears to be more effective in curing composites using camphorquinone (CQ) as an initiator compared to the QTH unit. A sufficient curing time (12 seconds) and an effective spectrum of light for composite curing may lead to a higher degree of polymerization in addition to higher linear shrinkage in these materials. However, the higher degree of conversion in the composite does not always lead to better physical properties.

In this study, the speed of polymerization was always higher in the PAC unit than the QTH cure (Figure 3a,b,c; Table 3). The reason for the more rapid cure appears to be related to the higher power density of the PAC unit. A linear relationship between light intensity and the amount of polymerization contraction has been demonstrated (Sakaguchi & others, 1992). Therefore, it is assumed that the high power density of the curing light determined the initial cure rate of polymerization.

It was suggested that a composite cured at a lower power density exhibited superior marginal adaptation (Uno & Asmussen, 1991a). However, this procedure leads to inferior material properties (Uno & Asmussen, 1991a). Another way to minimize the wall-to-wall contraction is to allow the resin composite to flow during setting, using controlled polymerization. This can be accomplished by pre-polymerization at a low power density, followed by a final cure at a high power density (Mehl, Hickel & Kunzelmann, 1997). The reduced rate of polymerization may allow the material to flow more easily and decrease the amount of polymerization shrinkage stress in a restoration (Uno & Asmussen, 1991b), which may be more favorable for marginal integrity (Feilzer & others, 1995; Mehl & others, 1997). The influence of the power density of a curing light on the marginal integrity of the cavosurface margin may differ, according to the types of composites. Cavalcante and others (2003) reported that the conventional technique for polymerization, used in association with a packable resin composite, provided a similar resin-tooth interfacial seal to a Soft-Start system and a better seal when compared to a PAC system. However, polymerization techniques showed the same result for a microhybrid resin composite. The speed of composite polymerization might have a greater effect on the composite-tooth margin in the packable composite, which has a relatively high elastic modulus.

In this study, a linometer was used to measure the speed and amount of polymerization. From the onset of this study, it became known that the PAC unit cured packable composites faster than a QTH unit, and short curing time in PAC, which the manufacturer recommended, resulted in a lower shrinkage value than the QTH-cured composite. Even though Park and others (2002) reported the possibility that the amount of linear shrinkage measured with a linometer could represent the degree of cure of composite, it is still technique sensitive (Park & others, 2002). Microhardness measurements are closely related to the degree of conversion for a composite, and they provide effective ways for evaluating the degree of curing (Rueggeberg & Craig, 1988). In this study, microhardness measurement was conducted to measure the degree of cure of the packable composite more objectively and accurately. TMPT was tentatively set for the microhardness study, because the curing time for the PAC system, recommended by the manufacturer, was shown to be inadequate based on the linometer study.

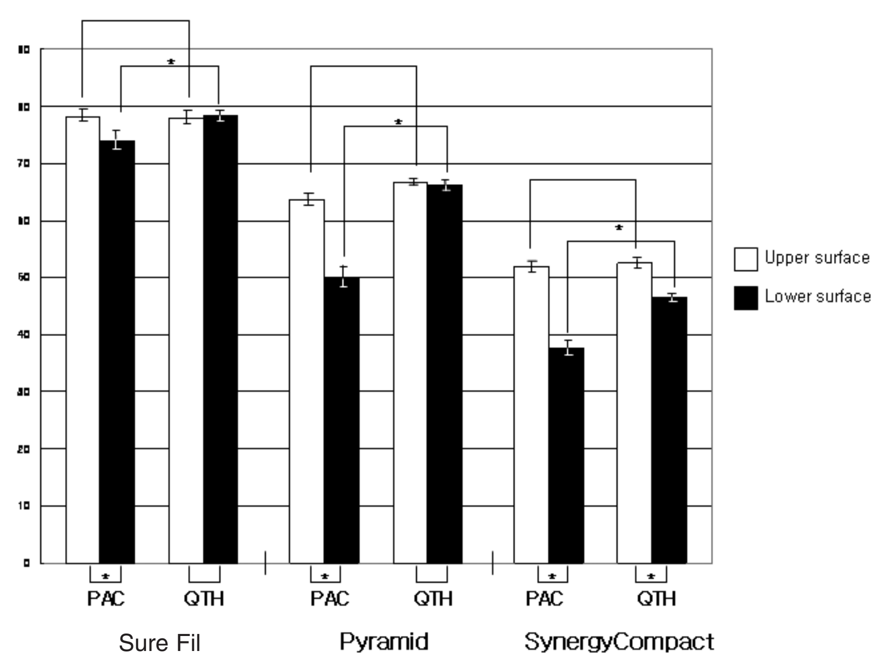

Figure 4. *Microhardness on the upper and lower surfaces of 2-mm thick PAC-cured or QTH-cured packable composites. * indicates a significant difference in microhardness at* p*=0.05 level.*

Table 2: *Amount of Linear Shrinkage in 60 Seconds (µm)*

Group	Sure Fil	Pyramid	Synergy Compact
1	3.8(0.6)a	5.5(0.6)a	6.0(0.9)a
2	4.7(0.6)b	6.8(0.6)b	6.3(0.8)a
3	5.5(0.4)c	7.7(0.4)c	7.1(0.8)b
4	5.8(0.5)c	10.3(0.4)d	8.6(0.9)c
5	6.4(0.4)d	11.5(0.4)e	10.2(0.5)d
6	6.7(0.3)d	10.4(0.7)d	8.7(0.7)c

Different letters indicate different amount of linear shrinkage at p*=0.05 level*

In this study, when the specimens were cured for 6 or 12 seconds (TMPT) using the PAC system, the microhardness of the lower surface of the 2-mm specimens did not reach the microhardness of the upper surface (Figure 4). This is consistent with the results reported by Park and others (2002). Specimen thickness for the linear shrinkage measurement was 1.3 mm; whereas it was 2 mm for the microhardness measurements.

Table 3: *Maximum Speed of Polymerization Shrinkage (S_{max}) and Peak Time(PT)*

		G1	G2	G3	G4	G5	G6
Sure Fil	S_{max}	1.4(0.4)b	1.6(0.4)b	1.8(0.5)b	1.5(0.5)b	1.7(0.5)b	0.8(0.2)a
	PT	1.05(0)a	1.6(0.5)b	1.05(0.5)b	1.6(0.5)b	1.6(0.5)b	3.8(0.5)c
Pyramid	S_{max}	1.9(0.4)b	2.4(0.3)c	2.2(0.3)c	2.7(0.4)d	2.9(0.4)d	1.5(0.3)a
	PT	1.05(0)a	1.6(0)b	1.6(0)b	2.15(0)c	2.15(0)c	3.8(0.5)d
SynergyCompacty	S_{max}	1.8(0.3)b	2.1(0.3)c	2.2(0.3)c	2.1(0.3)c	2.5(0.4)d	1.1(0.2)a
	PT	1.6(0)a	1.6(0)a	1.6(0)a	2.15(0)b	2.15(0)b	4.35(0.5)c

TMPT, which was adequate for a 1.3 mm specimen, may be insufficient for curing the lower surface of a 2 mm specimen. Some recent studies have indicated the possibility of an improper cure when the composites are light cured using a PAC unit (Peutzfeldt, Sahafi & Asmussen, 2000; Stritikus & Owens, 2000; Hofmann & others, 2000). An insufficient energy density may be the main reason for the insufficient cure. The duration of exposure will allow the excited CQ molecules to diffuse and react with the amine to help initiate polymerization. Moreover, the duration of exposure becomes important, particularly when the power density is not the rate-limiting step in polymerization (Rueggeberg & others, 1994). A relative short curing time in the PAC unit may be insufficient for the CQ molecule to diffuse to the deeper portions, which would then limit the reaction with the amine (Park & others, 2002). Park and others (2002) also suggested that a too rapid cure on the upper composite surface, which can act as a pre-cured overlay, might block light transmission through it and inhibit polymerization of the lower surface. Overall, the composite restoration will not cure adequately in the deeper portions if cured according to the recommendations of the PAC system manufacturer, who recommends a three-second cure.

It has been reported that composite curing of a deep cavity layer is considered complete if the minimum hardness value is >80% of the maximum value measured on the specimen surface (Lutz, Krejci & Frischknecht, 1992; Breeding, Dixon & Caughman, 1991). The microhardness value on the lower surface was less than the upper surface in all PAC-cured specimens. Of the samples, the microhardness of the lower surface of Sure Fil was > 80% of the upper surface hardness value; whereas it was below the value for Synergy Compact and Pyramid. The TMPT was 12 seconds for Sure Fil and 6 seconds for Synergy Compact and Pyramid. Therefore, the 12-second curing time for the PAC system may be acceptable if the layer thickness is within 2 mm.

In this study, a significant interaction also existed between the curing methods and observation surface for all materials ($p<0.05$). This was due to a significant difference in microhardness between Groups 1 and 2 on the lower surface; whereas there was no difference on the upper surface for all materials.

In a cavity, the direction of polymerization shrinkage of a light curing composite is relatively complex in the upward and central direction (Suh & Wang, 2001). However, the situation is different from the cavity in terms of the linometer set-up. The composite specimen for the linometer has three surfaces; upper, which is covered with a glass slide under pressure; lower, which is in contact with a movable disk and a lateral unbonded surface. Due to friction between the glass, composite specimen and disk, the central and downward movement of the monomer, which may occur in a cavity during the polymerization process, is restricted. Therefore, the specimen shrinks in the upward uni-direction in the linometer, and both the pre- and post-gel shrinkage could be measured (Davidson & Feilzer, 1997). A relationship was found between the magnitude of linear shrinkage and the correlation between the bonded (top and bottom) to unbonded (cylinder jacket) sample surface. As the ratio increases, the amount of linear shrinkage approaches volumetric shrinkage (Davidson & Feilzer, 1997).

The prevailing part of the increase in hardness was observed in the first few minutes after irradiation (Hansen, 1983). Although some authors have found that the optimum microhardness of the composites' resin surface was achieved after up to one month (Watts, McNaughton & Grant, 1986), Pilo and Cardash (1992) reported that post-irradiation microhardness at the bottom and top surfaces increased for up to one day and showed no further increase after one day. In this study, microhardness was measured seven days after light curing, and the samples were stored in a light proof box.

CONCLUSIONS

The use of the PAC system in a packable composite resulted in a more rapid cure compared to when they were cured using the QTH system. The microhardness of the lower surface of the 2-mm thick packable composites did not reach the microhardness of the upper surface, with 6 to 12 seconds of curing using the PAC system.

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