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Laboratory Research

The Effect of Energy Application Sequence on the Microtensile Bond Strength of Different C-factor Cavity Preparations

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Clinical Relevance

Light curing of resin composites in high C-factor cavity preparations using a high irradiance energy application sequence may lead to decreased bond strength. However, the high irradiance energy application sequence did not result in lower bond strengths in lower C-factor cavity preparations.

SUMMARY

This study investigated the effect of three equivalent radiant exposure energy application sequences (EASs): high intensity power (HIP: 1,177 mW/cm², 40 seconds), low intensity power (LOP: 573 mW/cm², 71 seconds) and ramp (RMP: 650 mW/cm², 5 seconds, then the irradiance increases to 1047 mW/cm², 37 seconds) on the microtensile bond strength (MTBS) in both low and high C-factor cavity preparations. Thirty Paradigm blocks (Z100) were mounted in stone, with their top surfaces parallel to the mounting block. High C-factor (HC=3.8) Class I cavity preparations were then prepared in 15 of the Paradigm blocks using a computer-controlled specimen former. Low C-factor (LC = 1.8) Class II cavity preparations were prepared in the remaining 15 blocks by sectioning them perpendicularly using a slow-speed diamond saw. Five samples, one from each experimental group (3 EASs x 2 C-factors), were prepared and stored in the dark for 48 hours in distilled water at 37°C prior to MTBS testing on the third day and on the remainder of the samples (n=30). Mode of fracture was determined with a stereomicroscope at 20-40x magnification. The findings of this study

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indicated that HC, in combination with HIP, had significantly lower bond strength (27.54 MPa) than LC with HIP (51.39 MPa). On the other hand, there was no significant difference between high and low C-factors with the other EASs (LOP or RMP). There was also no significant effect for EAS (HIP, RMP and LOP), with C-factor (HC or LC) held constant. The HIP-HC group had the highest percentage of adhesive (20%) and mixed adhesive (50%) failures (70% total). Adhesive and mixed adhesive failures occurred in other groups, but with lower percentages (RMP-LC: 40% total) (LOP-HC: 40% total).

INTRODUCTION

Polymerization shrinkage is one of the most important and clinically relevant problem associated with photopolymerization. For every mole of carbon-carbon double bond conversion of the methacrylate-based resin composite monomer into carbon-carbon single bond to form the polymer, there is 23 cubic centimeters of shrinkage.[1] The amount of conversion of monomer into polymer depends on the total energy applied to the resin composite. Total energy or radiant exposure (formerly referred to as energy density) is the product of irradiance (units = mW/cm^2, formerly referred to as power density) and time (units = s) and is expressed in J/cm^2 or mJ/cm^2.

Polymerization shrinkage of resin composites is of clinical importance because of transient and residual stresses that are introduced during restoration of the tooth. Polymerization shrinkage stress does not depend solely on the volumetric contraction of the resin composite, but also on the elastic modulus of the composite and the tooth,[2] cavity design[3] and the extent to which the restoration remains bonded to the tooth. Polymerization shrinkage stress is positively correlated with irradiance,[4] and the rate of force development is also linearly related to irradiance.[5] High irradiance curing lights, with their resulting higher forces and force rates, have been found to have a negative effect on the integrity of the restoration-cavity interface.[6-7]

Several strategies have been proposed to decrease polymerization shrinkage, including placement of low-modulus liners or bases, incremental placement of resin composite and placement of initial increments of chemically cured composites. There is no conclusive data on the efficiency of the incremental placement technique in reducing the contraction stresses of resin composite. A finite element analysis study conducted by Versluis and others suggests that the incremental composite restoration filling technique may actually result in higher polymerization shrinkage effects than the bulk filling technique.[8]

New methodologies of light application, so called "soft-start" methods, have been developed in order to overcome problems associated with polymerization shrinkage. These strategies include a low initial irradiance followed by a stepped or ramped increase to higher irradiance or a short, low irradiance pulse followed several minutes later by a longer exposure to high irradiance. Extended exposure times at low irradiance have also been shown to result in decreased shrinkage stress[9] and improved marginal fidelity.[6] These energy application sequences (EASs) describe the application sequence, timing and irradiance for each step or steps used in the light application. The purported reason for using these techniques is to lengthen the pre-gelation phase by lowering the polymerization rate, thus providing more time for the resin composite to flow, relieve stress[10] and, subsequently, result in an improved adaptation of the resin composite. When comparing different EASs, one must be sure that similar degrees of conversion have been achieved, since contraction force is proportional to the degree of conversion.[11] The exposure duration of the EASs being evaluated can be modified so that equivalent radiant exposures result in similar degrees of conversion for proper light-curing of the resin composite.[12-13]

Several studies have found that the soft-start polymerization technique was effective in reducing gap formation in resin composite restorations.[14-17] It is assumed that improved marginal fidelity in prior studies is a result of lower shrinkage stress, and several studies have found that soft-start light curing can reduce the polymerization contraction stresses transferred to the tooth-restoration interface.[5,18-21]

Another factor that may play a role in the development of contraction stresses and, thus, the adaptation of the resin composite to the bonded cavity walls, is the C-factor, which is the ratio of the bonded to unbonded surface area.[3] Increasing the C-factor has been associated with an increase in the development of shrinkage stresses[3] and, subsequently, an adverse effect on bond strength.[22-24]

Most of the studies that investigated the effect of the light-curing mode on bond strength have utilized shear bond strength tests with low C-factor configurations.[25-26] The use of microtensile bond strength allows sampling of a specific interface in cavity preparations with high or low C-factors. e Silva and others utilized microtensile bond strength testing to investigate the effects of EAS on bond strengths in high C-factor preparations. This study found that stepped light intensity resulted in higher MTBS values compared to a conventional single-intensity curing mode. There was no significant difference between the pulse-delay and conventional light-curing modes.[27]

This study investigated the effect of low, high and ramped irradiance energy application sequences on microtensile bond strength in both low and high C-factor preparations. The working hypotheses studied were: (1) The bond strength of resin composite to Paradigm substrate will be higher when the initial irradiance is lower, as with the ramped cure mode or, if the entire exposure is at a lower irradiance (mW/cm^2), as the rate of stress formation is slower and may potentially be compensated for by flow. Initial or continued low irradiance was compensated for by increased irradiation time(s), so that all EASs resulted in equivalent radiant exposure (mJ/cm^2). (2) The bond strengths of resin composites to Paradigm substrate will be improved irrespective of EAS (assuming equal radiant exposure) as the C-factor (resultant stress) decreases. While the interaction effect of C-factor on EAS is unknown, it would be expected that, if EAS has an effect, it would be more pronounced with a higher C-factor.

Table 1: *Average irradiance and adjusted exposure times resulting in equivalent radiant exposure for high power (HIP), low power (LOP), and ramp (RMP) energy application sequences (EAS).*

EAS	Average Power (W)	Spot Size (cm^2)	Average Irradiance (mW/cm^2)	Exposure Duration (s)	Radiant Exposure (J/cm^2)
HIP	506	0.43	1177	40	46.9
LOP	246	0.43	572	71	46.4
RMP	450	0.43	1047	42	46.4

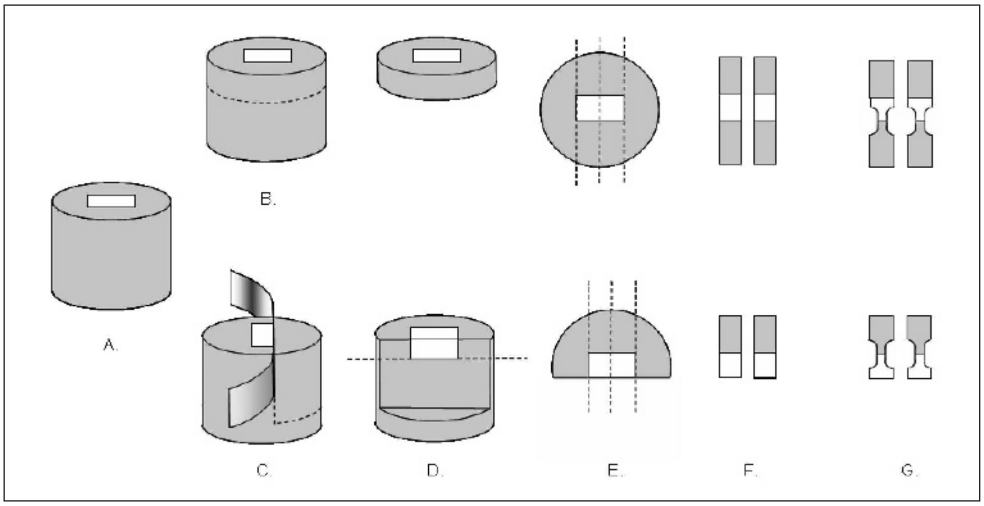

Figure 1. *Specimen preparation to obtain tensile specimens. A: Paradigm cylinder with 2.00 x 2.00 x 5.00 machined preparation. B: High C-factor cavity preparation (HC, C=3.8). C: Low C-factor cavity preparation (LC, C=1.8) with vertical sectioning of cylinder to allow insertion of Mylar strip, which reduces bonded surface area. D: 2.00 mm thickness sectioned from top of specimen. E: Top view of sectioning to obtain sticks. F: Sectioned sticks G: Trimmed sticks.*

Paradigm blocks with highly-reproducible machined preparations were used as the bonding substrate to decrease the variability that is associated with bonding to dentin. Bonding to dentin has been found to be both adhesive and substrate dependent.[28-29]

METHODS AND MATERIALS

Three user-selectable cure modes (HIP, LOP, RMP) of a commercially available LED curing light (Bluephase, serial #1538474, Ivoclar Vivadent, Schaan, Liechtenstein) were modified to provide three energy application sequences (EASs) with equivalent radiant exposures (J/cm^2) and, therefore, similar degrees of conversion. An equivalent radiant exposure (J/cm^2) is critically important to the study design, since contraction stress is proportional to the degree of conversion.[13] Only one resin composite was tested, since, even with equivalent radiant exposures, stress and the degree of conversion would vary with different formulations. Heliomolar, which is generally considered a hard to cure composite, was tested, as a more highly photosensitive composite with too efficient a photoinitiator system may not result in a lower rate of polymerization or stress formation.[17-18]

Radiant exposure delivered from the high irradiance (1177 mW/cm^2) light-curing mode (HIP) over 40 seconds was used as the control. Radiant exposure for HIP EAS (46.9 J/cm^2) was calculated by dividing the power measured over 40 seconds by the spot size (0.43 cm^2). A relatively high radiant exposure was chosen, as Heliomolar is often viewed as a low stress material, because it is hard to cure and the level of conversion and the resulting stress is low with lower radiant exposures. Equivalent radiant exposures for the other EASs, which required more extended exposure durations, were calculated and verified experimentally using the Ophir NOVA Laser Power/Energy monitor and StarCom Software (version 2.04). These exposure durations (Table 1) were used to irradiate all subsequent samples.

Thirty Z100 Paradigm resin blocks, E shade (3M ESPE, St Paul, MN, USA), were mounted in stone, with their top surface parallel to the mounting block. High C-factor (2.00 x 2.00 x 5.00 mm, C=3.8) Class I cavity preparations were prepared in 15 of the Paradigm blocks using the University of Iowa CNC Specimen Former with a flat cylindrical medium grit diamond bur, #835. Low C-factor (2.00 x 2.00 x 5.00 mm, C= 1.8) Class II preparations were prepared in the other 15 blocks by sectioning them perpendicularly using a slow-speed diamond saw (Isomet 1000 Precision Saw, model #11-2180, Buehler, Lake Bluff, IL, USA) prior to machining the cavity preparations (Figure 1). As both the Class I and Class II preparations had similar dimensions and geometry, an equivalent volume of composite was used for both cavity preparations, and the same interface was tested for both C-factors.

The bonding surface of the Paradigm block was sandblasted for 2-3 seconds immediately before bonding using Precision Sandblaster, Model er/erc, (Danville Engineering Inc, Danville, CA, USA). The surface was acid etched with 35% H_3PO_4 for 15 seconds, rinsed for 30 seconds, then dried for 60 seconds. One drop of ceramic primer, RelyX (3M ESPE), was applied directly to the bonding surface and left to dry for 30 seconds. The Heliobond Syntac adhesive (Ivoclar/Vivadent) was applied with a brush and light cured for 10 seconds with HIP.

A C-clamp was used to hold a rectangular block and celluloid strip against the unbonded surface corresponding to the proximal surface of a Class II preparation in the low C-factor samples. This allowed for use of a similar condensation technique for the high and low C-factor groups and similar light orientation for equivalent irradiation of the resin composite surfaces. Shade A2 resin composite (Heliomolar, Ivoclar/Vivadent) was light-cured in bulk with each respective EAS.

All samples were light cured from the top using a celluloid strip between the light guide and the resin composite to prevent degradation of the radiant exitance. Irradiance was monitored throughout the experiment using an LED Demetron Radiometer (Kerr, Danbury, CT, USA).

Five samples, one from each experimental group (3EAS x 2C-factor), were prepared, then stored in the dark for 48 hours under distilled water at 37°C prior to sectioning and testing on the third day. The order of sample fabrication, sectioning and testing/sectioning/testing was reversed for each subsequent set of five samples, respectively, for all 30 samples.

Two sticks, 2.00 mm x 2.00 mm in cross-section, were sectioned from each sample using a slow-speed (100 rpm) diamond saw under constant water cooling (ISOMET 1000 Precision Saw, model No 11-2180, Buehler, Lake Bluff, IL, USA). The sticks were trimmed at the center of the paradigm/resin composite bonding interface with an 8-micron cylindrical diamond bur running longitudinally at 200,000 rpm with constant water cooling mounted in the University of Iowa CNC Specimen Former. The cross-sectional diameter of each specimen was measured with a digital caliper (Mitutoyo Corp, Kawasaki-shi, Japan) to the nearest 0.01 mm and ranged from 0.49 to 0.52 mm^2, with a gauge length of 1 mm. A passive gripping system (Dircks device), which possesses a matched radius of curvature to the test specimen (0.60 mm), was used to apply a tensile load. Each specimen was tested at 1 mm/minute until failure in a material testing machine (Zwick/Roell Model BZ2.5/TN1S, Zwick GmbH & Co, Ulm, Germany), with the stress to failure expressed in MPa.

After testing, the mode of fracture was determined by examining the specimens with a stereomicroscope under a range of 20 to 40x magnification. The mode of fracture was categorized as: 1) cohesive within Paradigm, 2) cohesive within resin composite, 3) within adhesive, 4) mixed with > 50% in Paradigm, 5) mixed with >50% in resin composite, 6) mixed with >50% in adhesive.

Descriptive statistics were calculated, and analysis of variance (ANOVA) and the post-hoc Tukey's studentized range (HSD) test were used to determine differences in bond strength among the groups, including assessment of possible interaction. All tests had a 0.05 level of statistical significance. SAS (version 9.1) software was used for the data analysis.

Table 2: *Mean microtensile bond strength for the C-factors with A: High power energy application sequence (HIP), B: Ramp energy application sequence (RMP) and C: Low power energy application sequence (LOP).*

C-factor	MPa (SD)	Tukey's Group Comparison
A: Mean microtensile bond strength for the C-factors with the high energy application sequence (HIP).		
LC	51.4 (27.5)	A
HC	27.5 (20.0)	B
B: Mean microtensile bond strength for the C-factors with the ramp energy application sequence (RMP).		
LC	58.7 (24.9)	A
HC	34.9 (26.8)	A
C: Mean microtensile bond strength for the C-factors with the low power energy application sequence (LOP).		
LC	33.2 (22.2)	A
HC	52.4 (32.5)	A

**Means with the same letter are not significantly different. Comparisons significant at the 0.05 level.*

RESULTS

Based on two-way ANOVA, the data showed a significant interaction effect between the EAS and C-factor on MTBS (p=0.0147). The results revealed that there was a significant effect for the level of C-factors (p=0.0398) on MTBS in the high power (HIP) group. Tukey's HSD tests showed that the mean MTBS for high C-factor (HC) (mean=27.54 MPa) was significantly lower than the mean MTBS for low C-factor (LC) (mean= 51.4 MPa), (Table 2A).

Table 3: *Mean microtensile bond strength of the energy application sequences at A: High C-factor level (HC), B: Low C-factor level (LC).*

EAS	MPa (SD)	Tukey's Group Comparison
A: Mean microtensile bond strength of the energy application sequences at the high C-factor level (HC).		
LOP	52.4 (32.5)	A
RMP	34.9 (26.8)	A
HIP	27.5 (20.0)	A
B: Mean microtensile bond strength of the energy application sequences at the low C-factor level (LC).		
RMP	58.7 (24.9)	A
HIP	51.4 (27.5)	A
LOP	33.2 (22.2)	A

**Means with the same letter are not significantly different. Comparisons significant at the 0.05 level.*

The difference in MTBS between low C-factor (58.7 MPa) and high C-factor (34.9 MPa) for the ramp (RMP) EAS approached significance (p=0.0543) (Table 2B). There was no statistical difference between low C-factor and high C-factor with the low power (LOP)-EAS (p=0.1413), (Table 2C).

The data also provided evidence that there was no significant differences among HIP, RMP and LOP EASs for either high C-factor (HC) (p=0.1248), (Table 3A) or Low C-factor (LC) (p=0.0813), (Table 3B).

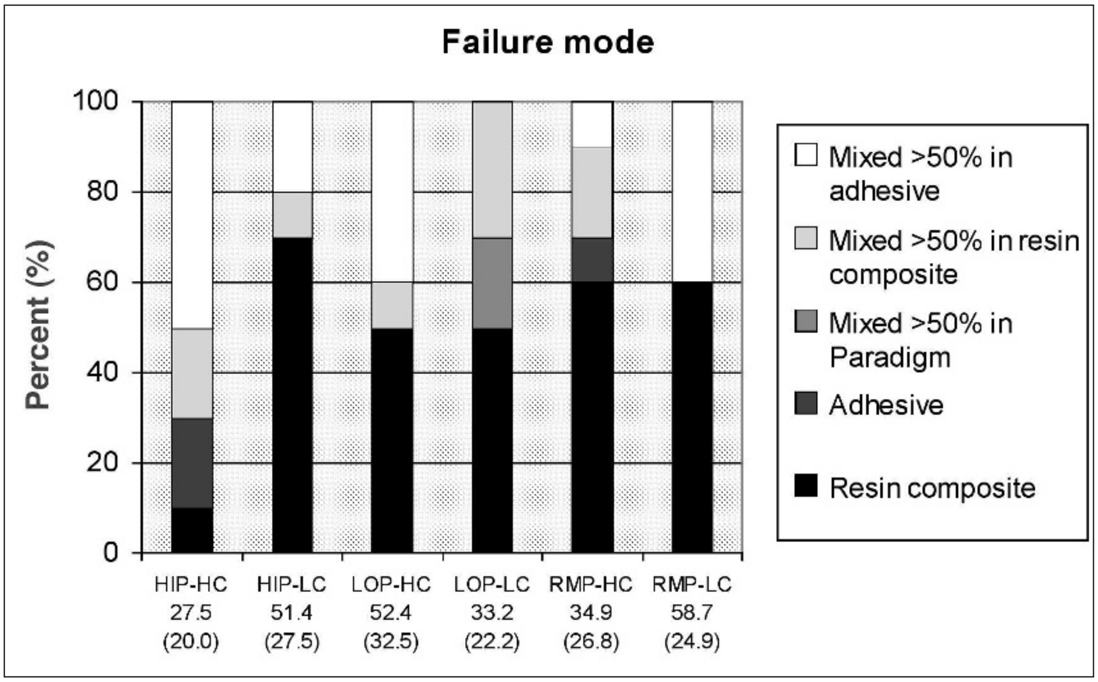

Figure 2*: Percentages of failure mode for each group of energy application sequence and C-factor (EAS-C- factor) and their corresponding mean microtensile bond strength [MPa (S.D)].*

Figure 2 summarizes the failure mode percentages of the debonded specimens in each EAS-C-factor group and their corresponding microtensile MTBS (SD) values. Most of the failures tended to occur cohesively in the resin composite. Pure or mixed failures (>50%) within Paradigm were the least common failure mode.

The HIP-HC group, which had the lowest bond strength, also had the highest percentage of adhesive (20%) and mixed adhesive (50%) failures (70% total). Adhesive and mixed adhesive failures occurred in other groups, but with lower percentages, (RMP-LC: 40% total), (LOP-HC: 40% total), (Table 3). All groups with higher bond strengths had 50% or more of their failures occur within the resin composite. There were no cohesive failures entirely within Paradigm and only one group (LOP-HC) had mixed failures of more than 50% within Paradigm.

DISCUSSION

The Paradigm CEREC blocks were used in this study as a substitute for dentin, as bonding to dentin has been shown to be material- and substrate-dependent. It is well known that bonding to superficial dentin has higher bond strength values compared to deep dentin.[29-31] Bonding to dentin is also technique sensitive and subject to operator variability.[32] A prefabricated material, such as Paradigm CEREC blocks that are fabricated under controlled and optimized manufacturing conditions, should therefore provide a more uniform substrate for bonding and was expected to reduce any variability that might be attributable to the bonding substrate.

Theoretically, the microtensile bond strength test should develop more even stress distribution than the shear bond strength test. However, stress distribution in the microtensile bond strength test has also been shown to be non-uniform. According to finite element analysis studies by Van Noort and others, the probability that defects in the adhesion interface may dominate the propagation of fracture during testing is very high due to interfacial stress distribution, especially at the edge of the interface.[33-34] Additional potential contributions to non-uniform stress distribution and the subsequent variability in observed results include: specimen geometry, gripping method and substrate properties. The dumbbell specimen used in this study has been demonstrated to have a superior stress distribution over the testing region as compared to an hourglass, and certainly, an untrimmed stick.[35] Also, the passive gripping device (Dircks device) used in this study does not employ any glue for fixation, which should reduce the possibility of any bending effect during tensile loading. However, it is unknown whether the testing methods employed exceeded customary allowable percent bending (<5%).[36] It is known that both the resin composite and Paradigm are relatively brittle substrates and, therefore, the reported strength values will be greatly influenced by any intrinsic flaws or defects in the bonded assembly.

Although there was a large numerical difference among means, this high variability may have contributed to the lack of significant differences among groups other than HIP-HC (p=0.0398). The test for simple effects for the C-factor with RMP-EAS approached significance (p=0.0543), as did the test for simple effects for EAS at low C-factor (p=0.0813). Paradigm, a supposedly more uniform substrate, failed to reduce bond strength variability. Although an attempt was made to reduce the occurrence by using CNC fabrication, it is possible that machining the preparations introduced defects such as microcracks or surface irregularities which influenced the results. Despite this, the microtensile bond strength test has been found to be reliable for testing resin cements bonded to processed composite substrate, such as Paradigm blocks.[37]

Energy application sequence (EAS) is a term used to describe the integrated area under the curve of irradiance, or power, (y-axis) plotted as a function of time (x-axis) that defines radiant exposure or product of irradiance and exposure duration. Soft-start curing methods have a reduced initial irradiance that supposedly allows the composite to flow before reaching the gel-point, thereby reducing the final polymerization stress.[38] User-selectable EAS sequences would have resulted in differing radiant exposures with differing degrees of conversion and, hence, differing amounts of shrinkage stress. The exposure durations of the four energy application sequences used in this study delivered equivalent radiant exposures, which should result in equivalent degrees of conversion[13] and thus equivalent total shrinkage stress.[5,39] Any reduction in shrinkage stress and associated improvement in bond strength should then be attributable to lower irradiance of the RMP and LOP EASs.

In this study, the bond strength of ramp EAS was not significantly lower than the standard high power EAS under both high and low C-factors. Those findings are in line with Caldwell and others, who found that there is no difference in shear bond strength between stepped and continuous light-curing modes.[26] Price and others, however, found that the shear bond strengths obtained with standard light were significantly greater than those obtained with stepped curing light using the Elipar Highlight light-curing device.[25] On the other hand, e Silva and others found that microtensile bond strength was higher when the soft-start light-curing mode was used compared to the conventional continuous light-curing mode.[27]

However, the radiant exposure of EASs is not always equivalent, as in the previously mentioned studies which evaluated the effect of EAS on bond strength.[25-26] This may be clinically relevant, as most clinicians do not compensate for an EAS with a lower overall radiant exposure by increasing exposure time. As a result, user-selectable EASs may result in a lower degree of conversion and lower stress, which would theoretically improve bond strength with soft-start EASs, or alternatively, they might improve bond strength with standard EASs due to improved degree of conversion.

Studies on the efficacy of soft-start light curing in reducing polymerization shrinkage vary and depend on the type of soft-start used in each particular study. While Yap and others found that pulse activation did not significantly reduce post-gel shrinkage,[20] Lim and others found that polymerization of resin composite using an initial low irradiance followed by a lag period before a final high irradiance resulted in reduction in polymerization shrinkage stress.[19] Stepped light-curing did not influence the rate and maximum polymerization shrinkage forces in studies by Bouschlicher and others and Yap and others.[40-41] Bouschlicher and Rueggeberg found that the rate of development of polymerization contraction stress and final shrinkage stress were effectively reduced using ramped light-curing.[18] Similarly, Ernst and others found that ramp light-curing reduced final polymerization contraction stresses.

It should be taken into consideration that the average radiant exposure used in this study (46.9 J/cm²) is relatively high compared with other studies that have shown a reduction in shrinkage stress. In addition, the results of this type of study are highly dependent on irradiance and photoinitiator concentration, and there is a narrow range within these variables where stress reduction can be achieved.[42] The effect of EAS was expected to more likely show up with a hard-to-cure composite, such as Heliomolar, which was selected for use in this study. A resin composite with higher photoinitiator concentration and/or greater light transmission in combination with a high irradiance light may defeat the stress relieving effects of soft start EASs. The effects of reduced curing rates on contraction stress are limited, and significant reductions in stress can be obtained if the curing rate drops below a certain threshold, with reduced irradiance in the early stages of photoinitiation.[17-18,42] It should be noted that, while Heliomolar is generally regarded as a low stress material, the high radiant exposure used in this study results (46.9 J/cm²) in higher stress levels than those typically obtained with lower irradiance lights using a similar 40-second exposure.

The microtensile bond strength of the LC (C=1.8) group was significantly greater than the bond strength of the HC group (C=3.8) in HIP EAS, which is in agreement with previous studies.[22-24,43-44] As the unbonded surface area increases, the ability of the resin composite to relieve contraction stresses by flow increases,[45-46] resulting in less disruption of the interface between the resin composite and the cavity wall.[47-48]

The only group that had more adhesive failure, either pure adhesive or mixed with >50% in adhesive, associated with lower bond strength, was HIP-HC (70%). This was expected, since the combination of high irradiance and high C-factor was expected to result in more shrinkage stresses being transferred to the cavity-restoration interface.[5,45] Low compliance systems, such as high C-factor cavity preparations, are expected to result in a higher degree of conversion.[49] As higher degrees of conversion result in greater shrinkage stress,[50] one might expect lower bond strengths due to greater disruption of the interface prior to MTBS testing. There was no general trend between lower bond strength values and adhesive failure mode noted within the other groups.

Although there was no statistically significant difference in MTBS between the EASs under high constraint (C=3.8), low power EAS (LOP, 573 mW/cm² x 71 seconds = 46.4 J/cm²) had the highest bond strength. This finding is in agreement with Uno and Asmussen, who found that a significant improvement in marginal adaptation could be obtained by polymerization at low irradiance.[10] This finding also agrees with another study by Uno and others, where the authors found that resin composite cured at a low irradiance with extended exposure times produced restorations that were well-adapted to dentin cavity walls.[14] Low irradiance was found to ameliorate polymerization shrinkage by extending the viscoelastic stage of the setting material and resulted in improved interfacial integrity.[6] Increasing exposure time to compensate for decreased irradiance results in a similar degree of conversion,[13] therefore, physical properties of the resin composite should not be affected.

If dentin is the substrate, high water content may act as heat sink and limits heat buildup. With Paradigm, the temperature increases associated with light curing and polymerization may have a greater effect on the compliance or constraint of the surrounding bonded substrate. Musanje and Darvell found that elevated temperature is associated with a decline in the elastic modulus of the resin composite; they speculated that the relaxation mechanism may exist at a low elastic modulus, which would allow stress relief to occur.[51] Increased heat buildup in the Paradigm block may cause relaxation of the polymer at the bonded interface, and this would be expected to enhance the bond strength of both C-factors. There was no statistical difference in bond strengths between the high and low C-factor with LOP, but the relative values are puzzling. While the radiant exposure for all EASs was equivalent, the longer exposure duration associated with LOP can result in greater heat buildup in the resin composite and surrounding substrate.[52] The extended exposure duration of the LOP EAS may have resulted in a difference in heat buildup, with resulting differences in thermal dimensional change of the walls adjacent to the open side of the LC preparation compared to the HC preparation. The open-side preparation used with low C-factor may have increased dimensional changes due to thermal expansion-contraction, with a resultant increase in disruption of the bonded interface and, hence, relatively lower bond strength. Measurements of relative expansion contraction of the open and closed C-factor configurations might clarify any role that differential expansion-contraction played in these results. Again, these factors may be unique to the use of a resin composite substrate and may not be applicable to dentin.

The results of this *in vitro* study may be specific to the resin composite and light curing unit utilized. Ernst and others stated that the effect of the soft-start curing mode depends on the resin composite, itself.[17] The same observation was also found by Lim and others, who discovered that the percentage of polymerization shrinkage reduction was different among the three resin composites which used the same soft-start light-curing mode.[19] Tests for the simple effects of C-factor with RMP-EAS approached significance (p=0.0543), as did the test for simple effects for EAS on low C-factor (*p*=0.0813). In these two instances, the conclusions drawn were based on strict interpretation of the statistical analysis, and increasing the sample size may have affected the results and the conclusions.

CONCLUSIONS

Within the limitations of this study, it was concluded that:

1. High C-factor resulted in significantly lower bond strength when resin composites were polymerized with high power EAS. There was an associated increase in adhesive failures within the HIP-HC group.
2. There was no significant difference in MTBS for high or low C-factor with low power-energy application sequences.
3. There was no significant difference in MTBS for high or low C-factor with ramp energy application sequences.
4. There was no significant difference in MTBS for energy application sequence at high C-factor.
5. There was no significant difference in MTBS for energy application sequence at low C-factor.

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References

1. Loshaek S & Fox TG (1953) Cross-linked polymers. 1. Factors influencing the efficacy of crosslinking in copolymers of methylmethacrylate and glycol dimethacrylate *Journal of the American Chemical Society* **75(14)** 3544-3550.
2. Dauvillier BS, Feilzer AJ, de Gee AJ & Davidson CL (2000) Visco-elastic parameters of dental restorative materials during setting *Journal of Dental Research* **79(3)** 818-823.
3. Feilzer AJ, de Gee AJ & Davidson CL (1987) Setting stress in composite resin in relation to configuration of the restoration *Journal of Dental Research* **66(11)** 1636-1639.
4. Peutzfeldt A & Asmussen E (2004) Determinants of *in vitro* gap formation of resin composites *Journal of Dentistry* **32(2)** 109-115.
5. Sakaguchi RL, Wiltbank BD & Murchison CF (2004) Contraction force rate of polymer composites is linearly correlated with irradiance *Dental Materials* **20(4)** 402-407.
6. Feilzer AJ, Dooren LH, de Gee AJ & Davidson CL (1995) Influence of light intensity on polymerization shrinkage and integrity of restoration-cavity interface *European Journal of Oral Sciences* **103(5)** 322-326.
7. Unterbrink GL & Muessner R (1995) Influence of light intensity on two restorative systems *Journal of Dentistry* **23(3)** 183-189.
8. Versluis A, Douglas WH, Cross M & Sakaguchi RL (1996) Does an incremental filling technique reduce polymerization shrinkage stresses? *Journal of Dental Research* **75(3)** 871-878.
9. Emami N, Söderholm KJ & Berglund LA (2003) Effect of light power density variations on bulk curing properties of dental composites *Journal of Dentistry* **31(3)** 189-196.
10. Uno S & Asmussen E (1991) Marginal adaptation of a restorative resin polymerized at reduced rate *Scandinavian Journal of Dental Research* **99(5)** 440-444.
11. Silikas N, Eliades G & Watts DC (2000) Light intensity effects on resin-composite degree of conversion and shrinkage strain *Dental Materials* **16(4)** 292-296.
12. Rueggeberg FA, Mettenburg DJ, Bouschlicher MR & Whalen S (2001) Evaluation of total energy concept: Microhardness testing *Journal of Dental Research* **80(AADR Abstracts)** Abstract #1742 p 253.
13. Halvorson RH, Erickson RL & Davidson CL (2002) Energy dependent polymerization of resin-based composite *Dental Materials* **18(6)** 463-469.
14. Uno S, Tanaka T, Natsuizaka A & Abo T (2003) Effect of slow-curing on cavity wall adaptation using a new intensity-changeable light source *Dental Materials* **19(2)** 147-152.
15. Yoshikawa T, Burrow MF & Tagami J (2001) The effects of bonding system and light curing method on reducing stress of different C-factor cavities *Journal of Adhesive Dentistry* **3(2)** 177-183.
16. Barros GK, Aguiar FH, Santos AJ & Lovadino JR (2003) Effect of different intensity light curing modes on microleakage of two resin composite restorations *Operative Dentistry* **28(5)** 642-646.
17. Ernst CP, Brand N, Frommator U, Rippin G & Willershausen B (2003) Reduction of polymerization shrinkage stress and marginal microleakage using soft-start polymerization *Journal of Esthetic & Restorative Dentistry* **15(2)** 93-103.
18. Bouschlicher MR & Rueggeberg FA (2000) Effect of ramped light intensity on polymerization force and conversion in a photoactivated composite *Journal of Esthetic Dentistry* **12(6)** 328-339.
19. Lim BS, Ferracane JL, Sakaguchi RL & Condon JR (2002) Reduction of polymerization contraction stress for dental composites by two-step light-activation *Dental Materials* **18(6)** 436-444.
20. Yap AU, Soh MS & Siow KS (2002) Post-gel shrinkage with pulse activation and soft-start polymerization *Operative Dentistry* **27(1)** 81-87.
21. Witzel MF, Calheiros FC, Goncalves F, Kawano Y & Braga RR (2005) Influence of photoactivation method on conversion, mechanical properties, degradation in ethanol and contraction stress of resin-based materials *Journal of Dentistry* **33(9)** 773-779.
22. Price RB, Derand T, Andreou P & Murphy D (2003) The effect of two configuration factors, time, and thermal cycling on resin to dentin bond strengths *Biomaterials* **24(6)** 1013-1021.
23. Armstrong SR, Keller JC & Boyer DB (2001) The influence of water storage and C-factor on the dentin-resin composite microtensile bond strength and debond pathway utilizing a filled and unfilled adhesive resin *Dental Materials* **17(3)** 268-276.

24. Loguercio AD, Reis A & Ballester RY (2004) Polymerization shrinkage: Effects of constraint and filling technique in composite restorations *Dental Materials* **20(3)** 236-243.
25. Price RB, Bannerman RA, Rizkalla AS & Hall GC (2000) Effect of stepped vs continuous light curing exposure on bond strengths to dentin *American Journal of Dentistry* **13(3)** 123-128.
26. Caldwell R, Kulkarni G & Titley K (2001) Does single versus stepped curing of composite resins affect their shear bond strength? *Journal of the Canadian Dental Association* **67(10)** 588-592.
27. e Silva AL, Pereira GD, Dias CT & Sartini Paulillo LA (2006) Effect of the composite photoactivation mode on microtensile bond strength and Knoop microhardness *Dental Materials* **22(3)** 203-210.
28. Toledano M, Osorio R, Ceballos L, Fuentes MV, Fernandes CA, Tay FR & Carvalho RM (2003) Microtensile bond strength of several adhesive systems to different dentin depths *American Journal of Dentistry* **16(5)** 292-298.
29. Pereira PN, Okuda M, Sano H, Yoshikawa T, Burrow MF & Tagami J (1999) Effect of intrinsic wetness and regional difference on dentin bond strength *Dental Materials* **15(1)** 46-53.
30. Yoshikawa T, Sano H, Burrow MF, Tagami J & Pashley DH (1999) Effects of dentin depth and cavity configuration on bond strength *Journal of Dental Research* **78(4)** 898-905.
31. Konishi N, Watanabe LG, Hilton JF, Marshall GW, Marshall SJ & Staninec M (2002) Dentin shear strength: Effect of distance from the pulp *Dental Materials* **18(7)** 516-520.
32. Miyazaki M, Onose H & Moore BK (2000) Effect of operator variability on dentin bond strength of two-step bonding systems *American Journal of Dentistry* **13(2)** 101-104.
33. Van Noort R, Cardew GE, Howard IC & Noroozi S (1991) The effect of local interfacial geometry on the measurement of the tensile bond strength to dentin *Journal of Dental Research* **70(5)** 889-893.
34. Van Noort R, Noroozi S, Howard IC & Cardew G (1989) A critique of bond strength measurements *Journal of Dentistry* **17(2)** 61-67.
35. Phrukkanon S, Burrow MF & Tyas MJ (1998) The influence of cross-sectional shape and surface area on the microtensile bond test *Dental Materials* **14(3)** 212-221.
36. *Annual Book of ASTM Standards* (2006) ASTM C 1273-05 Standard test method for tensile strength of monolithic advanced ceramics at ambient temperatures, Vol 15.01.
37. El Zohairy AA, de Gee AJ, Mohsen MM & Feilzer AJ (2003) Microtensile bond strength testing of luting cements to prefabricated CAD/CAM ceramic and composite blocks *Dental Materials* **19(7)** 575-583.
38. Mehl A, Hickel R & Kunzelmann KH (1997) Physical properties and gap formation of light-cured composites with and without "soft-start polymerization" *Journal of Dentistry* **25(3-4)** 321-330.
39. Calheiros FC, Braga RR, Kawano Y & Ballester RY (2004) Relationship between contraction stress and degree of conversion in restorative composites *Dental Materials* **20(10)** 939-946.
40. Bouschlicher MR, Rueggeberg FA & Boyer DB (2000) Effect of stepped light intensity on polymerization force and conversion in a photoactivated composite *Journal of Esthetic Dentistry* **12(1)** 23-32.
41. Yap AU, Ng SC & Siow KS (2001) Soft-start polymerization: Influence on effectiveness of cure and post-gel shrinkage *Operative Dentistry* **26(3)** 260-266.
42. Braga RR & Ferracane JL (2002) Contraction stress related to degree of conversion and reaction kinetics *Journal of Dental Research* **81(2)** 114-118.
43. Choi KK, Ryu GJ, Choi SM, Lee MJ, Park SJ & Ferracane JL (2004) Effects of cavity configuration on composite restoration *Operative Dentistry* **29(4)** 462-469.
44. Akagawa H, Nikaido T, Burrow MF & Tagami J (2005) Influence of cavity configuration on the adhesion of two resin-based composites to pulpal floor dentin *American Journal of Dentistry* **18(4)** 233-236.
45. Davidson CL, de Gee AJ & Feilzer A (1984) The competition between the composite-dentin bond strength and the polymerization contraction stress *Journal of Dental Research* **63(12)** 1396-1399.
46. Feilzer AJ, de Gee AJ & Davidson CL (1990) Quantitative determination of stress reduction by flow in composite restorations *Dental Materials* **6(3)** 167-171.
47. Davidson CL & de Gee AJ (1984) Relaxation of polymerization contraction stresses by flow in dental composites *Journal of Dental Research* **63(2)** 146-148.
48. Feilzer AJ, de Gee AJ & Davidson CL (1993) Setting stresses in composites for two different curing modes *Dental Materials* **9(1)** 2-5.
49. Lu H, Stansbury JW, Dickens SH, Eichmiller FC & Bowman CN (2004) Probing the origins and control of shrinkage stress in dental resin composites. II. Novel method of simultaneous measurement of polymerization shrinkage stress and conversion *Journal of Biomedical Material Research B: Applied Biomaterials* **71B(1)** 206-213.
50. Venhoven BA, de Gee AJ & Davidson CL (1993) Polymerization contraction and conversion of light-curing BisGMA-based methacrylate resins *Biomaterials* **14(11)** 871-875.
51. Musanje L & Darvell BW (2004) Effects of strain rate and temperature on the mechanical properties of resin composites *Dental Materials* **20(8)** 750-765.
52. Bouschlicher MR, Whalen SR & Dawson DV (2002) Intrapulpal temperature increase with LED, QTH and plasma arc photoinitiation *Journal of Dental Research* **81(Special Issue A)** Abstract # 0510 p A-89.