Marginal Adaptation of Direct Class II Composite Restorations with Different Cavity Liners

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Clinical Relevance

The application of flowable composite as a liner may not improve marginal adaptation and is product dependent. Lining the cavity with a 1-mm-thick layer of a bonding agent improves marginal adaptation but, clinically, may be problematic.

SUMMARY

The aim of this study was to evaluate how cavity linings with different elastic modulus can influence the marginal adaptation (MA) of Class II composite restorations before and after thermo-mechanical loading.

Materials and Methods: Forty Class II cavities with margins extending 1 mm below the cement-enamel junction were prepared in extracted human third molars. In each group except the control group, a lining material of 1-mm thickness was applied to the bottom of the cavity and polymerized before placing the resin composite Herculite XRV Ultra (group A: control; group B: Premise Flowable lining; group C: Herculite XRV Ultra lining; and group D: Optibond FL lining). MA was evaluated (with a scanning electron microscope) before and after loading (200,000 loading cycles). Statistical analysis was done using the Shapiro-Wilks test, the analysis of variance test, and Duncan *post hoc* test at $p < 0.05$.

Results: Before loading, the percentages of continuous margins in dentin were superior ($p < 0.05$) for groups C and D (71.1% and 87.2%, respectively) compared to groups A and B (55.7% and 48.3%, respectively). After loading, group D (79.8%) was statistically superior in dentin compared to all of the other groups (43.6%, 35.9%, and 54.4%, respectively). In occlusal enamel, no significant difference was found between groups. The percentage of enamel fractures and the percentage of non-continuous margins in proximal enamel were high, with no significant difference between liners. It can be concluded that for the materials used in this study, a 1-mm-thick lining with an extremely low elastic modulus (2-3 GPa) could redistribute shrinkage stress. The

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use of a flowable composite did not significantly improve MA.

INTRODUCTION

Light-cured resin composites (RCs) benefit today by an increasing spectrum of indications; their application has been expanded to include the restoration of anterior tooth wear[1-6] and noncarious cervical lesions.[7-10] Therefore, RCs continuously face challenges associated with specific environments, such as high tensile stresses in cervical areas as well as increased expectations with regard to longevity. Long-term stability is considered to be affected to a significant degree by marginal integrity.[11-13]

The marginal seal of composite restorations represents an increasing concern. Over the years, *in vitro* evaluations of the performance of resin adhesives revealed that microleakage and gap formation, mainly at the dentin-composite interface, did not improve at the same rate as did bond strength values.[13-16] Independent of the bonding capacity of an adhesive system, it seems that adhesive restorations are far from assuring a perfect marginal seal, with degradation in time occurring regardless of the product used.[17] Marginal integrity is considered to be the result of several parameters related to the forces created by curing contraction, as bond strength alone could not be correlated to marginal adaptation (MA) in a study undertaken by Kemp-Scholte and Davidson.[18]

A consensus can be found in the literature with regard to the effect of curing contraction in restoration performance. As a result of the confinement of the restoration, curing contraction has been shown to generate strain along the tooth restoration complex, leading to pre-stressed obturations, which are more prone to long-term degradation. The unfavorable effects of polymerization contraction forces can be evaluated effectively by marginal analysis, as marginal gaps offer proof of the forces generated by polymerization shrinkage or by thermo-mechanical strain, exceeding the bond strength.[15] Other methods of assessing the effects of polymerization contraction are finite element analyses (FEA) of the stress distribution,[10,19-21] measurements of tooth deformation[22-27] and, recently, a three-dimensional (3D)-deformation analysis.[28]

The phenomenon of force development in contracting materials was first described in the dental literature by Bowen.[29] Later, the subject of polymerization contraction stress was studied in depth in an attempt to clarify the complex interaction among the many factors involved. An interplay of polymerization shrinkage, elastic modulus (E-modulus), viscous flow capacity, and conversion degree of the material as well as adhesive ability, cavity configuration, and tensile stresses exerted on the restoration[12,14,19,30-33] is considered responsible for the marginal integrity. The combined action of several factors creates various stresses on the restoration-tooth interface, with consequences such as debonding or strain on the remaining tooth structure creating enamel fissures, fractures,[34] and cuspal movement.[22,25,35] Authors of studies[20,23,27] employing the FEA method also developed maps of polymerization stress accumulation, showing the distribution patterns of the forces and the effect on remaining tooth structures.

The dimensional modification due to shrinkage depends on the number, size, and functionality of the monomers as well as on the filler load. The volumetric contraction undergoes two phases: the phase before and the phase after the gel point. During the first phase, the resin retains its capacity to flow, and, therefore, it compensates the contraction forces by rearrangement of the molecules by preventing strain that would otherwise develop at the interfaces. During the second phase, however, the contraction forces are directed toward the bonded surfaces, leading to, among other things, defects in the MA. These defects occur when the elasticity of the material is not sufficient to compensate for the contraction forces, thus allowing for stress to develop at the interface of the tooth restoration complex. High strain capacity (reduced E-modulus), high viscous flow, and small amounts of polymerization shrinkage lead to reduced gap formation.[19]

Extensive research was done on the implications associated with the E-modulus of the restorative material. Flexibility is defined as the ability of a material to strain without becoming permanently deformed.[36] The higher the E-modulus and the polymerization shrinkage of the composite, the higher the contraction stress will be.[12,20,23,37] According to physical laws and *in vitro* observations, a low E-modulus is supposed to play an important role in stress relief, becoming, therefore, a desired property of the material.[19,20] It is assumed that an increased flexibility would lower stress values on the interface.[19,20] However, both the E-modulus and contraction are related to the filler content: a higher filler load would lead to a lower contraction but to an increase in stiffness as well.[12,14,31,36,38] A way to overcome this difficulty within material composition involves the use of a flexible material as liner under

the restorative material, giving rise to the 'elastic wall' theory. Based on the hypothetical benefits of increasing the compliance of the prepared cavity artificially, low-modulus intermediate layers such as flowable RCs and unfilled adhesives were presented as stress breaking materials.[33,36,38,39]

Different studies[18,20,37,40] measured stress relief when an unfilled resin with increased thickness was used as intermediate stress breaker, and an FEA study[20] was able to create a stress map of the tooth-restoration complex measuring different stress relief values for different thicknesses of the adhesive layers. However, studies evaluating the influence of flowable composites placed as intermediate layers on marginal integrity show conflicting results. Based on previous research, a general opinion prevails indicating that the behavior of a material as a stress absorber cannot be predicted using the E-modulus alone, as polymerization kinetics is a complex material-specific phenomenon.[12,38,41] Therefore, controversy is still present in the literature regarding the supposed positive effect of flowable composites on stress relief and marginal integrity.

Despite this high relativity, some hypotheses have been promoted and need further investigation. Accordingly, some authors[19,37,42] suggest the use of an extremely low E-modulus in order to obtain a significant effect, while others[37,42] suggest placing a pre-cured layer on top of the adhesive regardless of the composition (restorative or flowable RC).

The null hypothesis tested was that no difference in terms of percentage of continuous margin (% CM) exists among restorations with liners of different elasticity. The independent variables that were kept constant were loading condition (before and after loading), cavity lining (no lining; Optibond FL liner; Herculite XRV Ultra; and Premise Flowable) and tooth substrate (occlusal enamel [OE]; proximal enamel [PE]; and cervical dentin [D]). The only tested variable was MA, expressed in % CM.

MATERIALS AND METHODS

Cavity Design

Forty Class II occluso-mesial cavities, with margins extending 1 mm below the cemento-enamel junction, were prepared in extracted human third molars (for each tooth only one cavity was prepared). The teeth were stored in 0.1% thymol solution, and after scaling and pumicing, teeth were randomly assigned to four experimental groups (n=10) and mounted on custom-made specimen holders using a cold polymerizing resin (Technovit 40721, Haereus Kulzer,

Wehrheim, Germany). Prior to the mounting, the apices were sealed with an adhesive system (Optibond FL, Kerr, West Collins, CA, USA). Diamond burs (80 μm; Universal Prep set, Intensiv SA, Lugano, Switzerland) were used under continuous water spray. The standardized dimensions for the proximal cavity were as follows: width = 5 mm, height = 6 mm (measured from the tip of the palatal cusp to the gingival margin), depth = 2 mm (mesio-distal width of the gingival floor). For the occlusal cavity, the dimensions were as follows: depth = 3.5 mm (measured from the tip of the palatal cusp) and width (vestibule-oral dimension) = 5 mm.

Materials

For all groups, a nano-hybrid composite (Herculite XRV Ultra) was used for the restoration. A three-step etch-and-rinse system (Optibond FL) with a proven bonding capacity, a 48% filler load, and a very low E-modulus was used as the adhesive. The flowable composite Premise Flowable was chosen for its low polymerization shrinkage relative to other flowable composites and for its high percentage of filler load, assuring good mechanical properties as the lining material is in direct contact with the oral environment (Figure 1). All of the above-mentioned materials were provided by the same manufacturer, therefore assuring compatibility. The properties of the mentioned materials are listed in Table 1.

Restorative Procedures

Restoration was performed immediately after cavity preparation in order to avoid alteration of dental tissues. All cavities were beveled in the occlusal box.
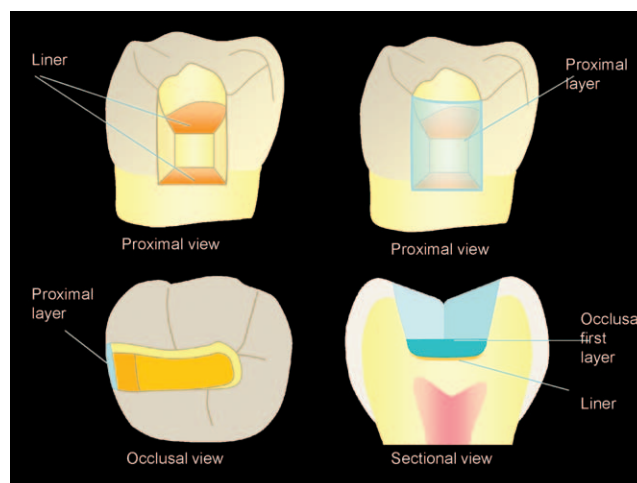

Figure 1.   *Application of the liner and layering technique of the RC.*

Table 1: *Material Properties*[a]			
Material	**Elastic Modulus, GPa**	**Volumetric Polymerization Shrinkage, %**	**Filler Load by Weight, %**
Herculite XRV Ultra	9.4	2.7	78
Premise Flow	7.55	3.31	72.5
Optibond FL	1-3	—	48[a]
[a] Data provided by the Kerr Corporation.			

The teeth were randomly assigned to one of the four groups, as follows.

Group A (Control Group)

The cavities were encircled with a metallic matrix band after conditioning enamel and dentin with a 37% H_3PO_4 gel (Gel Etchant, Kerr) for 45 seconds and 15 seconds, respectively. Dental tissues were rinsed and nearly dried with a light air pressure spray (two to three seconds) before the application of the two adhesive components (Primer and Adhesive), following the manufacturer's instructions. The bonding resin was light-cured (Bluephase, Ivoclar Vivadent, Schaan, Liechtenstein) for 40 seconds. This step was preceded by the buildup of the proximal wall with a unique vertical increment of less than 1-mm thickness (centripetal layering technique). The vertical increment of the proximal box was cured for 40 seconds from the occlusal direction. The matrix band was then removed, and the composite resin was applied using a three-increment layering technique for the occlusal cavity (Figure 1). Each increment in the occlusal cavity was 1.5 mm thick and was individually cured for 40 seconds (light intensity produced by the curing device = ~1000 mW/cm^2).

Group B

The same steps were performed as for group A. After polymerization of the adhesive system, a thin lining layer of Premise Flowable (1-mm thickness) was applied on the bottom of the occlusal cavity and the proximal box (exposed to external environment) and polymerized before the buildup of the proximal wall. The occlusal cavity was further filled, after removal of the matrix band, using the same composite, Herculite XRV Ultra, and the same layering technique as described for group A (Figure 1).

Group C

The same steps were performed as for group A until cavity restoration. After polymerization of the adhesive system, a thin lining layer of the restorative composite Herculite XRV Ultra (1-mm thickness) was applied on the bottom of the occlusal cavity

and the proximal box and was polymerized before buildup of the proximal wall. The occlusal cavity was further filled after removal of the matrix band using the same composite, Herculite XRV Ultra, and the same layering technique as described for group A (Figure 1).

Group D

The same steps were performed as for group A until cavity restoration. After polymerization of the adhesive system, a thick layer of the adhesive from the Optibond FL adhesive system (1-mm thickness) was applied as lining material on top of the same Optibond FL adhesive system and was polymerized before the buildup of the proximal wall. The occlusal cavity was further filled after removal of the matrix band using the same composite, Herculite XRV Ultra, and the same layering technique as described for group A (Figure 1).

Evaluation

Seventy-two hours after polymerization, the restorations were finished and polished using flexible disks with different grain sizes (SofLex PopOn, 3M-ESPE, St Paul, MN, USA). Immediately after completion of the polishing procedure, impressions were made of each restoration with a polyvinyl-siloxane impression material (President Light Body, Coltene, Alstätten, Switzerland). Subsequently, epoxy replicas were prepared for the computer-assisted quantitative marginal analysis in a scanning electron microscope (SEM; XL20, Philips, Eindhoven, The Netherlands) at 200× magnification. Continuous margins were assessed separately in D (% CM in D), PE (% CM in PE), and OE (% CM in OE), as percent of the total length of the analyzed margins. Total margin length represents the data from all of the margins of a Class II cavity, which is composed of OE, PE, and D. Additionally, enamel fractures (EF) parallel to the margins were documented in the SEM.

After storage at 37°C in water in the dark for two months, the restored teeth were loaded with repeated thermal and mechanical stress in a chewing

Table 2: *Percentage of Continuous Margins (%CM) Located in Dentin*[a]

Group	Description	Before Loading (mean $\pm$ SD)	After Loading (mean $\pm$SD)
A	Control (Optibond FL + Herculite XRV Ultra)	55.7 $\pm$ 25.1 b,c	43.6 $\pm$ 28.2 b
B	Opotibond FL + Premise Flowable + Herculite XRV Ultra	48.3 $\pm$ 21.8 c	35.9 $\pm$ 28.6 b
C	Optibond FL + Herculite XRV Ultra + Herculite XRV Ultra	71.1 $\pm$ 27.8 a,b	54.4 $\pm$ 29.6 b
D	Optibond FL + Optibond FL + Herculite XRV Ultra	87.2 $\pm$ 19.4 a	79.8 $\pm$ 25.4 a

Abbreviation: SD, standard deviation.
[a] Different letters indicate significant differences between groups of the same column (p<0.05). The lowest values of marginal continuity were obtained for groups A and B. Before loading, groups C and D were significantly superior compared to groups A and B but were not significantly different compared to each other. After loading, results showed no difference in marginal adaptation (MA) among groups A, B, and C, with group C being clearly superior.

machine. Thermo-cycling was carried out in flushing water with temperature changing 600 times from 5°C to 50°C and back with a dwell time of two minutes at each temperature. The mechanical stress comprised 200,000 load cycles transferred to the center of the occlusal surface with a frequency of 1.7 Hz and a maximal load of 49 N. Epoxy replicas were prepared for the computer-assisted quantitative marginal analysis in a SEM, using the same parameters as were used before the loading procedure.

Statistical analysis was done using the Shapiro-Wilks test, and differences between groups were statistically evaluated using analysis of variance and the Duncan *post hoc* test at $p<0.05$. The difference between results related to loading conditions (before and after the fatigue test) was analyzed using the statistical method of the paired *t*-test. MA was the only dependent variable.

RESULTS

Only the means and standard deviations for the percentages of CM and EF are reported, as 'overfilled margins' and 'underfilled margins' did not exceed 5% in any group. The scores for the MA are displayed separately for PE, D, and OE in Tables 2 through 5.

Before loading, the MA in cervical D was superior ($p<0.05$) for groups C and D compared to groups A and B. In PE and OE, all groups showed the same behavior ($p>0.05$) and it was noticed that the % CM

in PE was relatively low compared to the % CM in OE (Tables 2 through 5).

After two months of water storage and after thermal and mechanical stressing, the MA decreased considerably in all four groups at a statistically significant level. A paired-samples test showed significant differences ($p=0.000$) between both testing intervals before and after loading in all of the marginal segments tested (occlusal, proximal, and terminal).

Significant differences between groups were found for the criteria % CM in D and % CM in PE. In D, the superiority of the group D was clearly outlined ($p<0.05$) compared to all of the other three groups (Table 2). In PE, significant superiority was found only for group C compared to group A, with no statistically significant difference between the other liners. The % of enamel fractures (% EF) was high after loading, the application of the liners showing no statistically significant improvement of the MA (Table 5).

All restorations, both with and without lining material, presented discontinuous margins. The null hypothesis could be rejected, as statistically significant differences could be demonstrated between groups.

DISCUSSION

The present study was designed to test the classical presumption about the positive effect of flowable composite liners (Premise Flowable in this experi-

Table 3: *Percentage of Continuous Margins (%CM) in Proximal Enamel (PE) Before and After Loading*[a]

Group	Description	Before Loading, mean $\pm$ SD	After Loading, mean $\pm$ SD
A	Control (Optibond FL + Herculite XRV Ultra)	78.6 $\pm$ 3.5 a	30.3 $\pm$ 14.1 c,b
B	Opotibond FL + Premise Flow + Herculite XRV Ultra	79.2 $\pm$ 23.7 a	35.5 $\pm$ 23.5 b,a
C	Optibond FL + Herculite XRV Ultra + Herculite XRV Ultra	79.6 $\pm$ 16.4 a	48.6 $\pm$ 14.5 a
D	Optibond FL + Optibond FL + Herculite FL	71.1 $\pm$ 16.1 a	45.5 $\pm$ 9.4 b,a

Abbreviation: SD, standard deviation.
[a] Different letters indicate significant differences between groups of the same column (p<0.05). The % of CM in PE was low before and after loading. The comparison between groups reveals a significant difference only for group C compared to group A and only after loading. No significant difference was found among the three different liners.

Table 4:	*Percentage of Continuous Margins (%CM) in Occlusal Enamel (OE) Before and After Loading*[a]		
Group	**Description**	**Before Loading, mean ± SD**	**After Loading, mean ± SD**
A	Control (Optibond FL + Herculite XRV Ultra)	92 ± 13.7	84.5 ± 21.8
B	Optibond FL + Premise Flow + Herculite XRV Ultra	94 ± 10.4	87.3 ± 20.1
C	Optibond FL + Herculite XRV Ultra + Herculite XRV Ultra	98.5 ± 2	92.2 ± 6.7
D	Optibond FL + Optibond FL + Herculite XRV Ultra	97.3 ± 3.6	88.6 ± 8.3
Abbreviation: SD, standard deviation. [a] No significant difference in %CM in OE was found between groups either before or after loading.			

ment) and to gain a better understanding of the influence of the E-modulus on marginal sealing of composite restorations before and after artificial mechanical and thermal aging. For this purpose, the study was designed to include a group with a pre-cured layer of an extremely elastic material, such as the adhesive of the adhesive system Optibond FL, as well as a group with a thin lining (1-mm thickness) of the same restorative composite used for the filling (Herculite XRV Ultra). The significant difference between the E-modulus of the three different cavity linings could therefore add more to the knowledge of marginal sealing of composite restorations than could be gained by using only groups with different flowable composites as liners.

SEM is a widely used method with which to evaluate MA. Direct observation by SEM is difficult as a result of the vacuum procedure utilized during SEM, which causes cracks. By using a replica method, artificial gap formation can be avoided.[43] The specimens were polished after 72 hours and stored for two months before thermo-mechanical stressing in order to take into consideration the complex post-polymerization processes, such as ongoing contraction and stress relaxation by water absorption.[44,45]

While several other studies assessed the MA of restorative RC with and without a flowable liner through the dye penetration method, no marginal evaluation by SEM was done on a bonding product placed as liner (in this case the Adhesive of the Optibond FL adhesive system). Also unlike previous studies, our experiment was not designed to compare the effect of different flowable RC liners but rather to assess the influence of an E-modulus within a broad range (2-3 GPa and 9.4 GPa) (Table 1).

A group with the Herculite XRV Ultra used as a 1-mm pre-cured layer was introduced with the purpose of determining to which degree the improvement in MA is due to the pure layering procedure rather than to the properties of the lining materials.

Knowing the unpredictable effect on MA of a flowable composite placed as a liner, regardless of its E-modulus,[12,38,41,46] we preferred to use a flowable RC with rather optimized mechanical properties (high filler load), which could be beneficial to clinical use. Among other flowable RCs, the Premise Flowable has one of the lowest polymerization shrinkage rates, and the filler load is close to that of a restorative RC (72.5%).

The composite placement technique was chosen in order to minimize the polymerization shrinkage stress, especially at the cervical D wall. Therefore, a unique vertical layer was considered to have a minimal contact with the walls of the proximal box and a favorable ratio of unbonded to bonded surface.

The cavity configuration, the adhesive, and the restorative composite were kept constant, with the focus remaining on those parameters related to lining materials.

MA in Dentin

In dentin, the lowest values of marginal continuity were obtained for groups A (no liner) and B (Premise Flowable liner). The application of a thin liner (1

Table 5:	*Percentage of Enamel Fractures (%EF) Before and After Loading*[a]		
Group	**Description**	**Before Loading, mean ± SD**	**After Loading, mean ± SD**
A	Control (Optibond FL + Herculite XRV Ultra)	4.4 ± 4.8 a	20.6 ± 17.4 a
B	Optibond FL + Premise Flow + Herculite XRV Ultra	4.9 ± 7.7 a	38.8 ± 24.1 b
C	Optibond FL + Herculite XRV Ultra + Herculite XRV Ultra	9.5 ± 18.7 a	25.6 ± 16.3 a
D	Optibond FL + Optibond FL + Herculite XRV Ultra	10.7 ± 11.6 a	30.7 ± 14.8 a
[a] Different letters indicate significant differences between groups of the same column (p<0.05). The %EF in proximal enamel (PE) was high after loading. The comparison between groups reveals no differences before loading. After loading, group B was significantly worse (p=0.05) compared to groups A, C, and D, which were not significantly different to each other. A high standard deviation is to be noted as well as a significance level of only p = 0.05.			

mm) of Herculite XRV Ultra led to significantly superior MA in dentin only before loading and only compared to the control group, but this finding was not significantly different compared to group D ($p>0.05$). This result is probably due to the benefits of placing a pre-cured layer, as previously described.[37,42] It is worth noting that, while not always statistically significant, the group with Herculite XRV Ultra lining showed generally better MA than did the control group. However, group D was significantly better than all of the groups after loading, indicating that layering is not the only factor contributing to the stress relief (Table 2).

Applying the flowable RC as a liner did not achieve better MA. Before loading, group B was significantly worse than group C. After loading, results showed no difference in MA by using the flowable liner compared to the results achieved by layering the composite (group C) or compared to the control group results (group A). Both before and after loading, group B was significantly worse than group D. A possible explanation, presented by other authors[12,38,41] as well, indicates that the benefits of the elasticity of the flowable liner were probably surpassed by its contraction.

After thermo-cycling, a significant improvement of MA in dentin was obtained only by placing a 1-mm-thick layer of Optibond FL on top of the same bonding product (Table 3). A clear positive effect on MA was observed in dentin before and after loading. This positive influence could be explained by the very low E-modulus of the Adhesive of the Optibond FL system, in the range of 1 to 3 MPa, as was predicted by some authors[20,33,40] and in accordance with other *in vitro* studies[18,36,37] showing a positive effect of thick layers of unfilled resins used as stress breaking liners under restorative composites. One FEA analysis[47] revealed an interesting finding in Class V cavities, in which only a very low E-modulus (2 GPa) was shown to be capable of absorbing tensions along the tooth restoration interface and thus preserving the cohesive and adhesive integrity of the tooth restoration complex.

MA in Enamel

In this study, the adaptation to PE was low and decreased significantly after loading. Some considerations are to be made regarding the evaluation of marginal integrity in PE, as follows:

- In all groups, the % of CM in PE after loading was low compared to OE (Tables 3 and 4). The most important cause is probably the lack of beveling

PE, leading, therefore, to a weak adhesion prone to EF.[48] The comparison between groups reveals no differences in MA before loading as well as an almost significantly higher % EF for group B after loading ($p=0.05$), although at a high standard deviation. While the % CM in PE was generally very low, the only significant difference between groups was found after thermo-cycling in group C, which scored higher % CM compared only to group A. It should be noted that no significant difference was found among the three different liners. It would appear that in PE, the most influential on MA was the lack of beveling of the margin. Less important seems to be the type of liner, which was not placed directly on the PE margins. In this particular configuration, the Optibond FL liner seems to have only a local effect in its area of direct application, which is the cervical D margins.

- Contraction seems to contribute as well to the degradation of the marginal integrity. The paired-samples test showed significantly higher values for the % EF and significantly lower % CM in proximal cavities after thermo-cycling compared to before thermo-cycling. It is well documented[23] that areas pre-stressed by polymerization shrinkage show failure under occlusal load. Forces due to contraction created a residual strain within the tooth, leading, after loading, to the formation of cracks in the PE, a finding that is in accordance with those of the FEA analysis of Versluis and others.[27]

- Moreover, as a result of the cavity geometry, the axial enamel in a mesio-occluso-distal (MOD) cavity compensates less for deformation under load, compared to OE margins.[27] Under thermo-mechanical load, sound teeth distribute applied stresses more homogeneously compared to the structurally modified teeth, which show a complex biomechanical behavior due to the interruption of tissue continuity.[23,27,33] Therefore, the high percentage of noncontinuous margins in PE observed after loading could also result from a differential behavior, under load, of the PE walls compared to the OE margins when the continuity of a tooth is interrupted by a MOD cavity.

Therefore, the interaction between shrinkage stress distribution patterns[27,28] and biomechanical balance[23,27] of an occluso-proximal cavity under loading condition, together with strength of adhesion (bevel), creates a complex and differential behavior of proximal and occlusal tooth structures.

Shrinkage stress development is a dynamic, nonlinear process, depending on the complex inter-

action of many material-dependent, cavity-dependent, and restoration placement–dependent factors. Contraction stress in a tooth restoration complex reveals a distribution pattern with forces acting differently along the interface.[27] In this study, the highest percentage of noncontinuous margins was found in cervical D, which is in accordance with the stress distribution pattern depicted by FEA studies.[20,23,27] Polymerization stress maps showed shrinkage stress along the interface, with maximum stress accumulation at the cervical zone, in our case the dentin-composite interface, also known to be the most problematic area for adhesion.

The results of the present study confirm recent findings indicating that a thick adhesive layer with extremely low modulus could relieve stress at the interface, and they reaffirm the unpredictable stress-absorbing effect of flowable composites as liners. Research on properties of flowable composites also showed substantial differences in E-modulus and volumetric shrinkage, indicating flowable composites to be a very inhomogeneous group of materials.[12,38,41,46, 50-54] One study[38] situated the E-modulus in a wide range, with values between 6.5 GPa and 12.5 GPa for 12 different flowable composites. It seems that the performance of flowable composites as a stress buffer remains unpredictable, as polymerization kinetics tend to be material specific and because the optimization of the elasticity and shrinkage, with opposing effects, is difficult to achieve. In other words, despite their low E-modulus, the contraction stress produced by some flowable composites could be high because of their high volumetric shrinkage, which approaches 6% in some products.[12,38,41] Other studies[22,24,55-64] evaluating the influence of flowable composites placed as intermediate layers,[49] on marginal integrity show conflicting results as well.

Based on the present research, it seems that a liner with a very high elasticity applied in a thick layer could redistribute shrinkage stress and contribute to maintaining integrity along the tooth restoration interface, as indicated by previous research.[18,20,33,36,37,40]

Although the % CM after load in cervical D was higher in group D, the % EF in PE was not significantly lower compared to the other groups, indicating that enamel did not benefit from the same stress relief as did the interface. Our results correlate as well with those of other studies[16,18,50,51] reporting that a layer of low modulus composite can lead to redistribution of the forces and some strain relief along the interface but does not improve bond strengths and therefore does not reduce the overall negative influence of curing contraction. In the present study, the liner was applied only on the cervical margin and pulpal wall, not on the buccal and lingual proximal walls. It seems that the liner of Optibond FL was efficient in reducing and redistributing stress at the interface predominantly in the area of its application, where the marginal seal is also known to be the most problematic because of the concentration of stress, which is not uniformly distributed along the cavity walls.[20,21,23] This area is also marked by high variation in the bond strength along the bonded surface.[37,52] In return, no benefit of the stress-relieving effect was found on the enamel, where the bevel seems to play a more important role in assuring a good bonding stability after the fatigue test.

Any attempt to predict the contraction stress development of a material during polymerization based on E-modulus or polymerization shrinkage value alone seems to be misleading.[12,14,27,38,53] This hypothesis is confirmed as well by the present study, in which the flowable composite used as liner did not allow for the expected stress relief, while the performance of the Optibond FL liner was more heavily influenced by its very low E-modulus and was less affected by the high shrinkage. Product-specific properties such as flow capacity and pregel and postgel shrinkage render the stress-relieving effect unpredictable.

However, using only a composition-based approach to relieve shrinkage stress may still be too simplistic. Ensuring optimal dentin bonding and using incremental layers of composite in appropriate configurations are factors within the control range of the practitioner, which could be of importance in assuring a better marginal seal.[54] Accordingly, marginal quality could be optimized by factors such as guidance of the shrinkage vectors, reducing the ratio of bonded to free unbonded restoration surfaces, and minimizing the mass of *in situ*-cured composite.

CONCLUSION

For the materials used in this study, no improvement of MA was found when the flowable composite was used as a liner, both before and after thermomechanical loading. The application of a layer of the same restorative composite used for the restoration with the same thickness as the flowable composite (1 mm) had a positive effect before loading, probably as a result of the benefit of placing a precured layer on the bottom of the cavity before stratification of the

restoration. After thermo-mechanical loading, a significant improvement of MA in D was obtained only by placing a 1-mm-thick layer of the Adhesive of the Optibond FL system on top of the same product used as adhesive. This positive effect may be explained by its very low E-modulus, in the range of 1 to 3 MPa.

Conflict of Interest

The authors of this manuscript certify that they have no proprietary, financial, or other personal interest of any nature or kind in any product, service, and/or company that is presented in this article.

REFERENCES

1. Gow AM, & Hemmings KW (2002) The treatment of localized anterior tooth wear with indirect Artglass restorations at an increased occlusal vertical dimension. Results after two years *European Journal of Prosthodontic and Restorative Dentistry* **10(3)** 101-105.

2. Hemmings KW, Darbar UR, & Vaughan S (2000) Tooth wear treated with direct composite restorations at an increased vertical dimension: Results at 30 months *Journal of Prosthetic Dentistry* **83(3)** 287-293.

3. Poyser NJ, Briggs PF, Chana HS, Kelleher MG, Porter RW, & Patel MM (2007) The evaluation of direct composite restorations for the worn mandibular anterior dentition—Clinical performance and patient satisfaction *Journal of Oral Rehabilitation* **34(5)** 361-376.

4. Redman CD, Hemmings KW, & Good JA (2003) The survival and clinical performance of resin-based composite restorations used to treat localised anterior tooth wear *British Dental Journal* **194(10)** 566-572.

5. Schmidlin PR, Filli T, Imfeld C, Tepper S, & Attin T (2009) Three-year evaluation of posterior vertical bite reconstruction using direct resin composite—A case series *Operative Dentistry* **34(1)** 102-108.

6. Smales RJ, & Berekally TL (2007) Long-term survival of direct and indirect restorations placed for the treatment of advanced tooth wear *European Journal of Prosthodontic and Restorative Dentistry* **15(1)** 2-6.

7. Kubo S, Kawasaki K, Yokota H, & Hayashi Y (2006) Five-year clinical evaluation of two adhesive systems in non-carious cervical lesions *Journal of Dentistry* **34(2)** 97-105.

8. Peumans M, Kanumilli P, De Munck J, Van Landuyt K, Lambrechts P, & Van Meerbeek B (2005) Clinical effectiveness of contemporary adhesives: A systematic review of current clinical trials *Dental Materials* **21(9)** 864-881.

9. van Dijken JW, Sunnegårdh-Grönberg K, & Lindberg A (2007) Clinical long-term retention of etch-and-rinse and self-etch adhesive systems in non-carious cervical lesions. A 13 year evaluation *Dental Materials* **23(9)** 1101-1107.

10. van Dijken JW, & Pallesen U (2008) Long-term dentin retention of etch-and-rinse and self-etch adhesives and a resin-modified glass ionomer cement in non-carious cervical lesions *Dental Materials* **24(7)** 915-922.

11. Blunck U, & Roulet JF (1989) In vitro marginal quality of dentin-bonded composite resins in Class V cavities *Quintessence International* **20(6)** 407-412.

12. Dewaele M, Asmussen E, Devaux J, & Leloup G (2006) Class II restorations: Influence of a liner with rubbery qualities on the occurrence and size of cervical gaps *European Journal of Oral Sciences* **114(6)** 535-541.

13. Hilton TJ (2002) Can modern restorative procedures and materials reliably seal cavities? In vitro investigations. Part 2 *American Journal of Dentistry* **15(4)** 279-289.

14. Braga RR, & Ferracane JL (2004) Alternatives in polymerization contraction stress management *Critical Reviews in Oral Biology and Medicine* **15(3)** 176-184.

15. De Munck J, Van Landuyt K, Peumans M, Poitevin A, Lambrechts P, Braem M, & Van Meerbeek B (2005) A critical review of the durability of adhesion to tooth tissue: Methods and results *Journal of Dental Research* **84(2)** 118-132.

16. Irie M, Suzuki K, & Watts DC (2002) Marginal gap formation of light-activated restorative materials: Effects of immediate setting shrinkage and bond strength *Dental Materials* **18(3)** 203-210.

17. Bortolotto T, Ferrari I, & Onisor I (2005) Marginal adaptation of contemporary dentin bonding agents in enamel and dentin under the simulation of dentinal fluid *International Dentistry South Africa* **5(7)** 21-26.

18. Kemp-Scholte CM, & Davidson CL (1990) Marginal integrity related to bond strength and strain capacity of composite resin restorative systems *Journal of Prosthetic Dentistry* **64(6)** 658-664.

19. Asmussen E, & Peutzfeldt A (2008) Class I and Class II restorations of resin composite: An FE analysis of the influence of modulus of elasticity on stresses generated by occlusal loading *Dental Materials* **24(5)** 600-605.

20. Ausiello P, Apicella A, & Davidson CL (2002) Effect of adhesive layer properties on stress distribution in composite restorations—A 3D finite element analysis *Dental Materials* **18(4)** 295-303.

21. Kinomoto Y, & Torii M (1998) Photoelastic analysis of polymerization contraction stresses in resin composite restorations *Journal of Dentistry* **26(2)** 165-171.

22. Alomari QD, Reinhardt JW, & Boyer DB (2001) Effect of liners on cusp deflection and gap formation in composite restorations *Operative Dentistry* **26(4)** 406-411.

23. Ausiello P, Apicella A, Davidson CL, & Rengo S (2001) 3D-finite element analyses of cusp movements in a human upper premolar, restored with adhesive resin-based composites *Journal of Biomechanics* **34(10)** 1269-1277.

24. Cara RR, Fleming GJ, Palin WM, Walmsley AD, & Burke FJ (2007) Cuspal deflection and microleakage in premolar teeth restored with resin-based composites with and without an intermediary flowable layer *Journal of Dentistry* **35(6)** 482-489.

25. Suliman AA, Boyer DB, & Lakes RS (1993) Cusp movement in premolars resulting from composite polymerization shrinkage *Dental Materials* **9(1)** 6-10.

26. Tantbirojn D, Versluis A, Pintado MR, DeLong R, & Douglas T (2004) Tooth deformation patterns in molars after composite restoration *Dental Materials* **20(6)** 535-542.

27. Versluis A, Tantbirojn D, Pintado MR, DeLong R, & Douglas WH (2004) Residual shrinkage stress distributions in molars after composite restoration *Dental Materials* **20(6)** 554-564.

28. Chiang YC, Rösch P, Dabanoglu A, Lin CP, Hickel R, & Kunzelmann KH (2010) Polymerization composite shrinkage evaluation with 3D deformation analysis from micro CT images *Dental Materials* **26(3)** 223-231.

29. Bowen RL (1967) Adhesive bonding of various materials to hard tissues. VI. Forces developing in direct-filling materials during hardening *Journal of the American Dental Association* **74(3)** 439-445.

30. Braga RR, & Ferracane JL (2002) Contraction stress related to degree of conversion and reaction kinetics *Journal of Dental Research* **81(2)** 114-118.

31. Gonçalves F, Kawano Y, & Braga RR (2010) Contraction stress related to composite inorganic content *Dental Materials* **26(7)** 704-709.

32. Moreira da Silva E, dos Santos GO, Guimarães JG, Barcellos Ade A, & Sampaio EM (2007) The influence of C-factor, flexural modulus and viscous flow on gap formation in resin composite restorations *Operative Dentistry* **32(4)** 356-362.

33. Van Meerbeek B, Willems G, Celis JP, Roos JR, Braem M, Lambrechts P, & Vanherle G (1993) Assessment by nano-indentation of the hardness and elasticity of the resin-dentin bonding area *Journal of Dental Research* **72(10)** 1434-1442.

34. Kanca J III, & Suh BI (1999) Pulse activation: Reducing resin-based composite contraction stresses at the enamel cavo-surface margins *American Journal of Dentistry* **12** 107-112.

35. Bouillaguet S, Gamba J, Forchelet J, Krejci I, & Wataha JC (2006) Dynamics of composite polymerization mediates the development of cuspal strain *Dental Materials* **22(10)** 896-902.

36. Kemp-Scholte CM, & Davidson CL (1990) Complete marginal seal of Class V resin composite restorations effected by increased flexibility *Journal of Dental Research* **69(6)** 1240-1243.

37. Braga RR, Hilton TJ, & Ferracane JL (2003) Contraction stress of flowable composite materials and their efficacy as stress-relieving layers *Journal of the American Dental Association* **134(6)** 721-800.

38. Labella R, Lambrechts P, Van Meerbeek B, & Vanherle G (1999) Polymerization shrinkage and elasticity of flowable composites and filled adhesives *Dental Materials* **15(2)** 128-137.

39. Unterbrink GL, & Liebenberg WH (1999) Flowable resin composites as "filled adhesives": Literature review and clinical recommendations *Quintessence International* **30(4)** 249-257.

40. Choi KK, Condon JR, & Ferracane JL (2000) The effects of adhesive thickness on polymerization contraction stress of composite *Journal of Dental Research* **79(3)** 812-817.

41. Stavridakis MM, Dietschi D, & Krejci I (2005) Polymerization shrinkage of flowable resin-based restorative materials *Operative Dentistry* **30(1)** 118-128.

42. Kowalczyk P (2009) Influence of the shape of the layers in photo-cured dental restorations on the shrinkage stress peaks—FEM study *Dental Materials* **25(12)** 83-91.

43. Grundy JR (1971) An intra-oral replica technique for use with the scanning electron microscope *British Dental Journal* **130** 113-117.

44. Davidson CL, & de Gee AJ (1984) Relaxation of polymerization contraction stresses by flow in dental composites *Journal of Dental Research* **63(2)** 146-148.

45. Segura A, & Donly KJ (1993) In vitro posterior composite polymerization recovery following hygroscopic expansion *Journal of Oral Rehabilitation* **20(5)** 495-499.

46. Attar N, Tam LE, & McComb D (2003) Flow, strength, stiffness and radio-opacity of flowable resin composites *Journal of the Canadian Dental Association* **69(8)** 516-521.

47. Ichim IP, Schmidlin PR, & Li Q (2007) Restoration of non-carious cervical lesions. Part II. Restorative material selection to minimize fracture *Dental Materials* **23(12)** 1562-1569.

48. Schmidlin PR, Wolleb K, Imfeld T, Gygax M, & Lussi A (2007) Influence of beveling and ultrasound application on marginal adaptation of box-only Class II (slot) resin composite restorations *Operative Dentistry* **32(3)** 291-297.

49. Oliveira LC, Duarte S Jr, Araujo CA, & Abrahão A (2010) Effect of low-elastic modulus liner and base as stress-absorbing layer in composite resin restorations *Dental Materials* **26(3)** 159-169.

50. Heintze SD (2007) Systematic reviews: I. The correlation between laboratory tests on marginal quality and bond strength. II. The correlation between marginal quality and clinical outcome *Journal of Adhesive Dentistry* **1(Supplement 9)** 77-106.

51. Ilie N, Kunzelmann KH, & Hickel R (2006) Evaluation of micro-tensile bond strengths of composite materials in comparison to their polymerization shrinkage *Dental Materials* **22(7)** 593-601.

52. Shono Y, Ogawa T, Terashita M, Carvalho RM, Pashley EL, & Pashley DH (1999) Regional measurement of resin-dentin bonding as an array *Journal of Dental Research* **78(2)** 699-705.

53. Marchesi G, Breschi L, Antoniolli F, Di Lenarda R, Ferracane J, & Cadenaro M (2010) Contraction stress of low-shrinkage composite materials assessed with different testing systems *Dental Materials* **26(10)** 947-953.

54. Lutz F, Krejci I, & Barbakow F (1991) Quality and durability of marginal adaptation in bonded composite restorations *Dental Materials* **7(2)** 107-113.

55. Korkmaz Y, Ozel E, & Attar N (2007) Effect of flowable composite lining on microleakage and internal voids in Class II composite restorations *Journal of Adhesive Dentistry* **9(2)** 189-194.

56. Guéders AM, Charpentier JF, Albert AI, & Geerts SO (2006) Microleakage after thermo-cycling of 4 etch and rinse and 3 self-etch adhesives with and without a flowable composite lining *Operative Dentistry* **31(4)** 450-455.

57. Tredwin CJ, Stokes A, & Moles DR (2005) Influence of flowable liner and margin location on microleakage of conventional and packable Class II resin composites *Operative Dentistry* **30(1)** 32-38.

58. Lindberg A, van Dijken JW, & Hörstedt P (2005) In vivo interfacial adaptation of Class II resin composite restorations with and without a flowable resin composite liner *Clinical Oral Investigations* **9(2)** 77-83.

59. Ziskind D, Adell I, Teperovich E, & Peretz B (2005) The effect of an intermediate layer of flowable composite resin on microleakage in packable composite restorations *International Journal of Paediatric Dentistry* **15(5)** 349-354.

60. Chuang SF, Jin YT, Liu JK, Chang CH, & Shieh DB (2004) Influence of flowable composite lining thickness on Class II composite restorations *Operative Dentistry* **29(3)** 301-308.

61. Attar N, Turgut MD, & Güngör HC (2004) The effect of flowable resin composites as gingival increments on the microleakage of posterior resin composites *Operative Dentistry* **29(2)** 162-167.

62. Olmez A, Oztas N, & Bodur H (2004) The effect of flowable resin composite on microleakage and internal voids in Class II composite restorations *Operative Dentistry* **29(6)** 713-719.

63. Leevailoj C, Cochran MA, Matis BA, Moore BK, & Platt JA (2001) Microleakage of posterior packable resin composites with and without flowable liners *Operative Dentistry* **26(3)** 302-307.

64. Jain P, & Belcher M (2000) Microleakage of Class II resin-based composite restorations with flowable composite in the proximal box *American Journal of Dentistry* **13(5)** 235-238.