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# Ceramic Inlays and Partial Ceramic Crowns: Influence of Remaining Cusp Wall Thickness on the Marginal Integrity and Enamel Crack Formation *In Vitro*

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## Clinical Relevance

The minimum effective thickness of cusp walls with adhesively bonded ceramic restorations is not yet defined. According to this *in vitro* study, a cusp wall thickness of at least 2.0 mm at the base is recommended.

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DOI: 10.2341/08-34

## SUMMARY

**No information is currently available about what the critical cavity wall thickness is and its influence upon 1) the marginal integrity of ceramic inlays (CI) and partial ceramic crowns (PCC) and 2) the crack formation of dental tissues. This *in vitro* study of CI and PCC tested the effects of different remaining cusp wall thicknesses on marginal integrity and enamel crack formation. CI (n=25) and PCC (n=26) preparations were performed in extracted human molars. Functional cusps of CI and PCC were adjusted to a 2.5 mm thickness; for PCC, the functional cusps were reduced to a thickness of 2.0 mm. Non-functional cusps were adjusted to wall thicknesses of 1) 1.0 mm and 2) 2.0 mm. Ceramic restorations (Vita Mark II, Cerec3 System) were fabricated and adhesively luted to the cavities with Excite/Variolink II. The specimens were exposed**

**to thermocycling and central mechanical loading (TCML: 5000x5°C-55°C; 30 seconds/cycle; 500000x72.5N, 1.6Hz). Marginal integrity was assessed by evaluating a) dye penetration (fuchsin) on multiple sections after TCML and by using b) quantitative margin analysis in the scanning electron microscope (SEM) before and after TCML. Ceramic- and tooth-luting agent interfaces (LA) were evaluated separately. Enamel cracks were documented under a reflective light microscope. The data were statistically analyzed with the Mann Whitney U-test ($\alpha$=0.05) and the Error Rates Method (ERM). Crack formation was analyzed with the Chi-Square-test ($\alpha$=0.05) and ERM. In general, the remaining cusp wall thickness, interface, cavity design and TCML had no statistically significant influence on marginal integrity for both CI and PCC (ERM). Single pairwise comparisons showed that the CI and PCC of Group 2 had a tendency towards less microleakage along the dentin/LA interface than Group 1. Cavity design and location had no statistically significant influence on crack formation, but the specimens with 1.0 mm of remaining wall thickness had statistically significantly more crack formation after TCML than the group with 2.0 mm of remaining cusp wall thickness for CI. The remaining cusp wall thickness of non-functional cusps of adhesively bonded restorations (especially for CI) should have a thickness of at least 2.0 mm to avoid cracks and marginal deficiency at the dentin/LA interface.**

## INTRODUCTION

Indirect esthetic adhesive restorations, that is, ceramic inlays (CI) and partial ceramic crowns (PCC), have become clinically accepted restorations for posterior teeth with extended coronal destruction[1-2] and they are basically regarded as an alternative for the use of dental alloys.[3] Reasons for the failure of ceramic restorations include secondary caries, fracture of the ceramic restorations or remaining tooth substance, marginal deficiencies and postoperative sensitivity.[4-5]

Reasons for marginal deficiencies and tooth fractures include multiple stresses, which may develop over time as a result of thermal[6] or mechanical stresses.[7] The stress may be severe enough to result in a weakened bond of the luting material to both the ceramic and tooth.[8] Furthermore, the stress may exceed the elastic limits of the teeth and result in cracks of the tooth structures.[9] Although some authors[10] doubt that the presence of such cracks affects the functioning of teeth, it was shown that enamel cracks may progress toward a complete loss of the whole tooth wall, which would require a new restoration[11-12] or, in a worst case scenario, extraction of the tooth.[5,11] The presence of cracks in the tooth may be further compounded by the fact that teeth become more brittle with age and, therefore, more susceptible to cracking and fracture, especially if the tooth has been weakened by restorative procedures[7,9,11,13-14] or endodontic treatment.[11] The resistance to fracture of the restored tooth may be influenced by many factors, such as cavity dimension,[13,15] physical properties of the restoration material[16] and the luting system used.[8,15] In order to protect the weakened tooth, coverage of the cusp with partial or full crowns is recommended.[5,17] However, no information is currently available regarding the appropriate cavity wall coverage thickness.

Studies from inlays or partial crowns using dental alloys and the conventional luting technique are not applicable to the clinical situation for ceramic restorations.[18] Ceramic-based inlays and partial crowns are adhesively luted, which not only protects the ceramic, but it also reinforces the remaining dental hard tissues.[19-20] Resin cements used for luting are elastic and tend to deform, making them capable of absorbing stress.[21] One result is that, for PCC preparations, conventional retention forms[22-23] are not mandatory, because retention totally depends on adhesion to the dental tissues.[18]

Fracture resistance of the tooth has been primarily tested using basic laboratory methods, where increasing load is applied on the intended surface until fracture.[24-25] These methods use the acute single loading failure, but tooth fracture seems to result from the accumulation of repeated stresses during oral functioning.[25]

It was hypothesized that cusp wall thickness would affect the marginal integrity of CI and PCC restorations and enamel crack formation. The current study tested this hypothesis in an *in vitro* assay by evaluating the influence of two different cusp wall thicknesses on the marginal integrity of CI and PCC restorations and evaluating enamel crack formation. Repeated stress during oral function was simulated using thermo-mechanical-loading cycles.

## METHODS AND MATERIALS

### Sample Preparation

Figure 1 summarizes the procedures followed in the current study. Sixty-three extracted maxillary human molars stored in 0.5% chloramine solution after extraction were cleaned, mounted in Pattern Resin (GC Corporation, Tokyo, Japan) and stored in physiological saline solution until use. A control group of 12 specimens received no treatment. Diamond burs with an angle of 1.5° (Cerinlay Set, Intensiv, Viganello, Lugano, Switzerland) in a high-speed handpiece with sufficient water cooling were used to perform one of the following preparations on each tooth (Figure 2A/2B):

Ceramic inlays (CI):
Preparation of MOD-cavities (width about 5.0 mm/depth about 4.0 mm); oral (functional) cusp about 2.5 mm wall thickness.

Partial ceramic crowns (PCC):
Preparation of MOD-cavities (width about 5.0 mm/depth about 4.0 mm); oral (functional) cusp about 2.5 mm wall thickness; about 2.0 mm horizontal reduction of the oral cusp.

Proximal margins were placed 1 mm below the CEJ within cementum/dentin, with a depth of about 1.5 mm. Rounded internal line angles were prepared. Vestibular (non-functional) cusps were not covered. The cusp wall thickness of the vestibular cusps was adjusted to (Group 1): 1.0 mm and (Group 2): 2.0 mm (Figures 2A/2B). The CAD/CAM method (Cerec 3 software version 1.0, Sirona, Bensheim, Germany) was used to construct and machine-mill the CI and PCC from Mark II ceramic blocks (Vita, Bad Säckingen, Germany).

Following try-in and adjustment of the prepared cavities with Komet finishing diamonds (Brasseler, Lemgo, Germany) and sufficient water-cooling, the CI and PCC were inserted using Excite/Variolink II (Vivadent, Schaan, Liechtenstein), a dual-cured resin composite luting agent (12 or 13 specimens each per cavity design and the remaining cusp wall thickness). The restorative procedures were performed in a

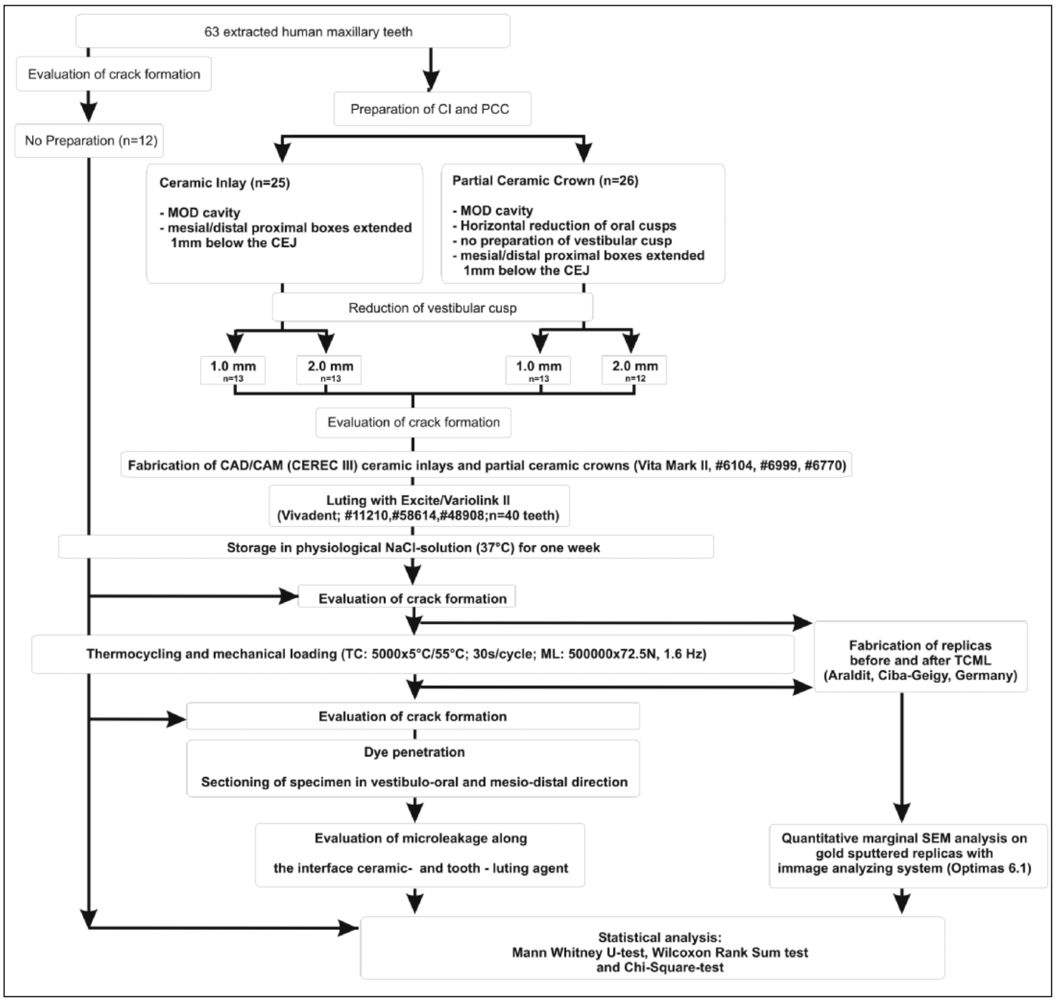


Figure 1. *Flow chart: methods and materials.*

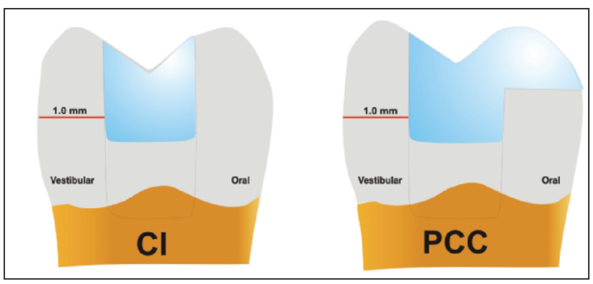


Figure 2A. *Schematic drawing ceramic inlay (CI) and partial ceramic crown (PCC) preparation, representing a midline cut in the vestibulo-oral direction.* Dotted lines *indicate proximal boxes below the CEJ and* red lines *indicate the thickness of the vestibular cusp wall of Group 1 (1.0 mm).*

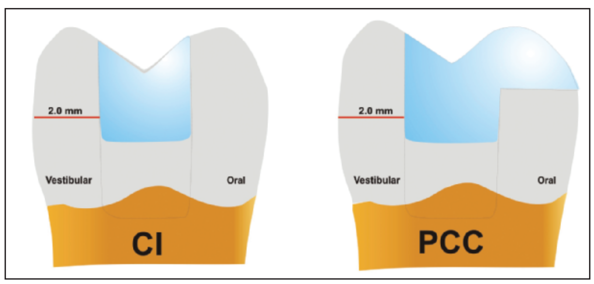


Figure 2B. *Schematic drawing ceramic inlay (CI) and partial ceramic crown (PCC) preparation, representing a midline cut in the vestibulo-oral direction.* Dotted lines *indicate proximal boxes below the CEJ and* red lines *indicate the thickness of the vestibular cusp wall of Group 2 (2.0 mm).*

device that simulated proximal contact of the adjacent teeth, matching the clinical situation as closely as possible. The luting material was applied to the cavity surfaces following adhesive conditioning of the dental tissues and ceramic restoration surfaces. The luting procedure of Excite/Variolink II is summarized in Table 1.

Table 1: *Luting Material, Cavity/Ceramic Conditioning and Instructions for Use*

| | |
|---|---|
| Luting material | Variolink II/VL<br>High viscosity, composite luting agent (Vivadent, Germany) |
| Conditioning of ceramic | 1. Ceramics Etch gel (Vita, Germany) 60 seconds, followed by rinsing with water<br>2. Monobond S (Vivadent, Germany) applied and dried after 60 seconds |
| Conditioning of cavity | 1. Total Etch (Vivadent, Germany) enamel 40 seconds, dentin 20 seconds.<br>2. water spray and gentle blow-drying<br>3. Excite (Vivadent, Germany) application<br>4. after 20 seconds gentle blow drying<br>5. light curing for 20 seconds |
| Curing mode | Dual-curing (light application for 40 seconds from each aspect) |

Excess luting material was removed prior to curing. Following the insertion procedures, finishing was performed with Komet finishing diamonds (Brasseler) and the restorations were polished with Sof-Lex flexible discs (3M, St Paul, MN, USA). Before TCML, samples were stored in a physiological saline solution at 37°C for 24 hours. The samples were submitted to thermocycling (5,000×5 at 55°C and 30 seconds/cycle) and central mechanical loading (500,000×72.5 N at 1.6 Hz) simultaneously. Central mechanical loading was performed with a cyclic (1.6 Hz) increase in pressure (72.5N) upon a metal stop representing the opposing cusp. The metal stop was placed in the occlusal central fissure of the restoration.

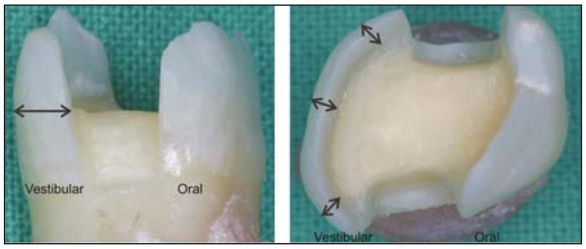


Figure 3A. *Example of determining the cusp wall thickness for a ceramic inlay (CI) preparation, arrows indicate measuring distances for the remaining cusp wall thickness of the vestibular cusp.*


Figure 3B. *Example of determining the cusp wall thickness for a partial ceramic crown (PCC) preparation, arrows indicate measuring distances for the remaining cusp wall thickness of the vestibular cusp.*

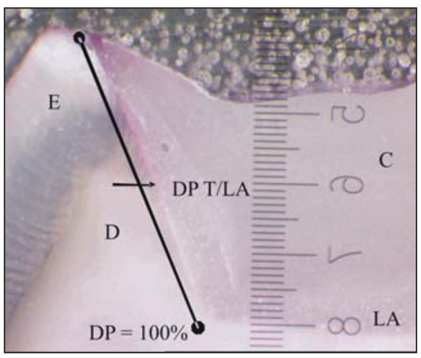


Figure 4. *Example of dye penetration (DP); C=ceramic; E=enamel; T=tooth; D=dentin; LA=luting agent; Arrow indicates dye penetration at the tooth/luting agent interface.*

## Determination of Cusp Wall Thickness

The actual tooth thicknesses of the vestibular cusp were evaluated before fabrication of the restoration and documented on three points (mesial, central and distal) at the bottom of the cavity for each specimen (Figures 3A/3B).

## Dye Penetration

Following TCML, microleakage at the oral, vestibular and proximal locations for ceramic- and tooth (enamel and dentin)-interfaces was determined separately by means of dye penetration. Except for areas within 1.0 mm of the restoration margins, the specimens were covered with nail varnish and placed in a 0.5% basic fuchsin solution for 16 hours at 37°C. After dye penetration with fuchsin, the specimens were cleaned, mounted onto stubs with acrylic resin and sectioned longitudinally in the mesio-distal direction and centrally in the vestibulo-oral direction (Figure 4) into as many approximately 300 µm-thick sections as possible,[4-8] using a rotating diamond saw (blade thickness 300 µm) (Innenlochsäge Leitz 1600, Leitz) with sufficient water cooling. Each section provided two sites for the evaluation of dye penetration. Digital images of the sections were used to measure microleakage, which was recorded using an image analyzing system (Optimas 6.1, Stemmer, Munich, Germany) at three locations: 1) the proximal cervical area (dentin-cementum), 2) the vestibular area (enamel) and 3) the oral area (enamel). Records were performed separately for the tooth/LA and ceramic-restoration/LA interfaces. The extent of dye penetration was expressed as a percentage of the entire length of the restoration wall

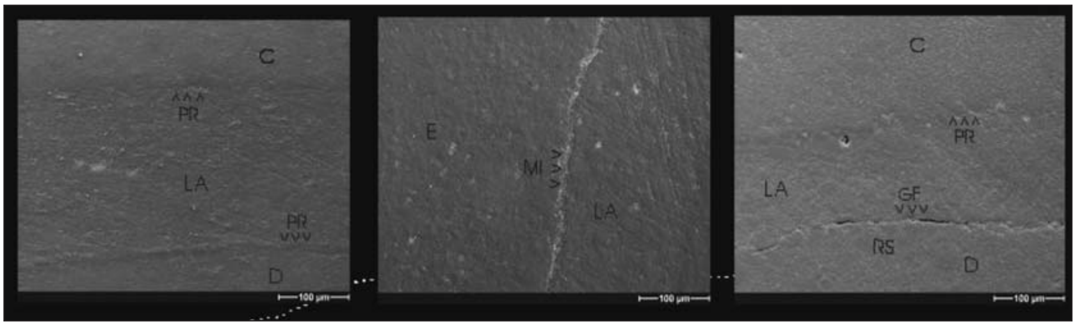


Figure 5. *Scanning electron microscopic picture indicating proximal restoration margins. Arrows indicate restoration margins denoted by perfect margin (PR), marginal imperfections (MI) and gap formation (GF). Ceramic (C), enamel (E), dentin (D), tooth-luting agent interface (LA)*

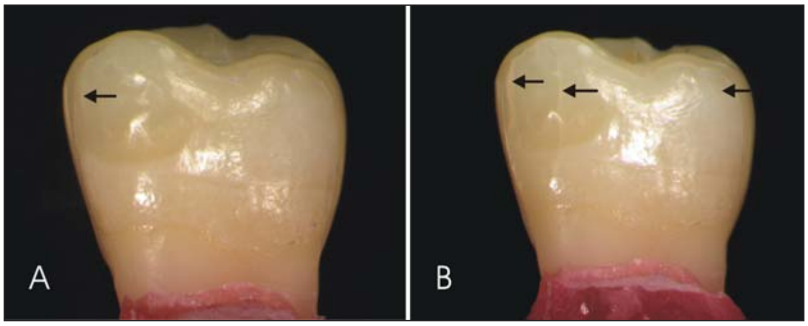


Figure 6. *Example of cracked tooth substance. Arrows indicate fracture lines. A: before TCML B: after TCML*

(100% reference) as shown in Figure 4. Four dye penetration measurements were recorded from each section, rendering 16-36 measurements per tooth (4x 4-8 sections/tooth). The maximum value was selected for each tooth and used for further statistical evaluations.

## Quantitative Scanning Electron Microscopic Analysis

The replicas representing the specimen before and after TCML were subjected to quantitative margin analysis at 200x magnification in a Stereoscan 240 scanning electron microscope (SEM) (Cambridge Instruments, Nussloch, Germany). Oral, vestibular and proximal restoration margins (Figure 5) registered on the replicas were included in the SEM evaluation. Tooth/LA and ceramic/LA interfaces were evaluated separately. The following criteria were used to describe margin quality:

A. Perfect margin (PM): perfect adhesion and continuous adaptation at the ceramic/LA or tooth/LA interface.

B. Marginal imperfections (MI): no gap, but marginal imperfection (that is, excess luting material, positive or negative ledges) due to the handling of LA.

C. Gap formation (GF): a clearly visible loss of adhesion between LA and ceramic or dental tissues.

D. Marginal expansion (ME): hygroscopic expansion at the tooth/LA interface; none of the above criteria can be applied.

The criteria of margin quality were assigned to the corresponding sections of each interface and calculated as percentages of the entire length of the restoration margin examined. Marginal imperfections (MI), gap formation (GF) and marginal expansion (ME) represented areas of compromised adhesion. Percentages of MI, GF and ME were added to compromised adaptation (CA). The percentages of CA were calculated and selected as a descriptive value, representing the extent of marginal deterioration at each interface. The results presented in the current data refer to criterion CA. SEM data were pooled for each remaining cusp wall thickness, location and cavity design by TCML and interface.

## Documentation of Cracks/Fractures

Visible cracks (Figure 6) discernable under a reflective light microscope (Wild Makroskop M420, Heerbrugg, Germany) at 12x magnification were evaluated and documented. After preparation (AP), before TCML (BT) and after TCML (AT), oral and vestibular digital images of the specimen were taken. Visible cracks of non-treated specimens (control group) were evaluated and documented both before and after TCML.

## Statistical Analysis

Non-parametric statistical analysis was considered appropriate for analyzing the data, because of the lack of symmetry. For marginal integrity as well as crack formation, medians and 25%–75% percentiles for each experimental group (n=12 or n=13) were determined for the different experimental conditions (remaining cusp wall thickness, location, cavity design and time for the SEM evaluation).

Marginal Integrity: All interfaces were considered separately. Statistical analysis was performed using the Mann-Whitney U and Wilcoxon Rank Sum tests (SPSS version 15.0; SPSS, Chicago, IL, USA) for pairwise comparisons among the experimental groups.

Crack Formation: Statistical analysis was performed using the Chi-Square-test (SPSS version 15.0) for the committed change of enamel crack formation (Δ) at different times (after preparation [AP] and after TCML [AT]) compared to before TCML (BT). The test parameter ΔAP/BT or ΔBT/AT with the expression ≤0 represented a reduction or no change and ΔAP/BT or ΔBT/AT with the expression ≥1 represented an increase in enamel crack formation. The frequency distribution of changes in crack formation Δ≤0 and Δ≥1 has been reported.

For marginal integrity and crack formation, the level of significance was set at $\alpha$=0.05. For generally evaluating the influence of several experimental groups, the level of significance was adjusted to $\alpha^*(k)=1-(1-\alpha)^{1/k}$ by application of the error rates method (k=number of paired tests to be considered).

## RESULTS

### Results of Dye Penetration

The results of dye penetration for ceramic inlays (CI) are summarized in Figure 7A and Table 2. For the experimental group "remaining cusp wall thickness" (1.0 mm and 2.0 mm), ERM and single pairwise comparisons showed no statistically significant differences in dye penetration. However, Group 2 (56.4%) showed a tendency towards less dye penetration at the dentin/luting agent (LA) interface than Group 1 (100%). For the experimental group "location" (oral and vestibular cusp), ERM and single pairwise comparisons showed no statistically significant difference in dye penetration between the locations. However, non-functional cusps (3.7-22.5%) revealed a tendency towards less dye penetration at the ceramic and enamel/LA interfaces than functional cusps (4.0-25.2%). For the experimental group "interface" (ceramic-, enamel- and dentin–LA), there was a significant difference (ERM) between interfaces. Ceramic (3.3-42.2%) and enamel/LA interfaces (13.2-25.2%) revealed significantly less dye penetration than the dentin/LA interface (56.4-100%), which was also shown in comparisons, for example, dye penetration at the proximal margin of Group 1 was statistically significantly higher ($p$=0.0065) at the dentin/LA interface (100%) than at the ceramic/LA interface (17.4%).

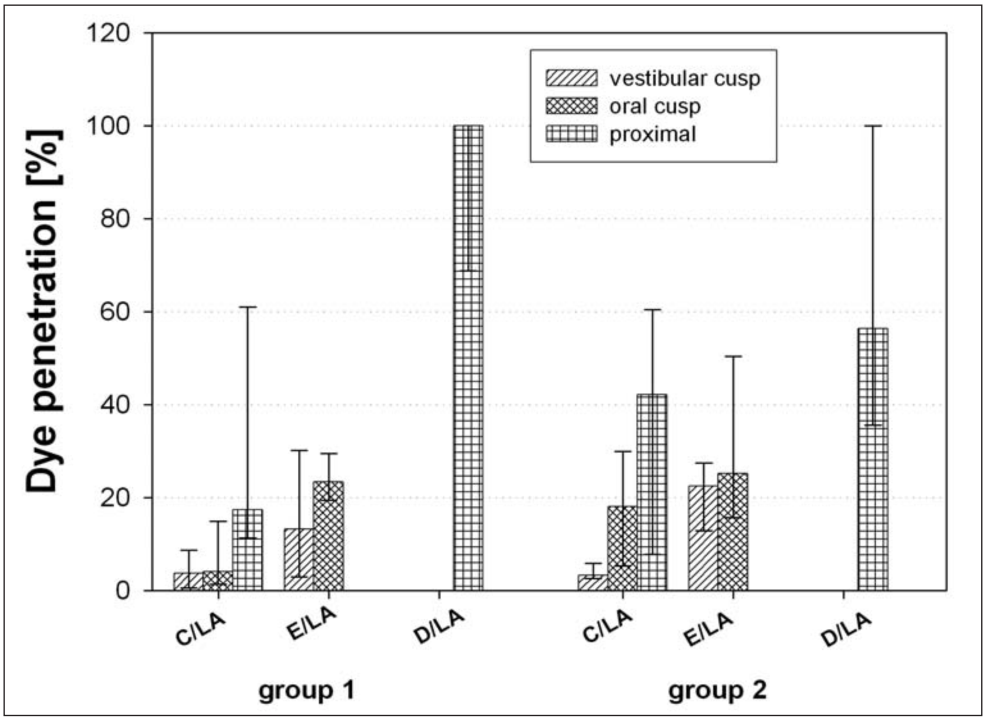


Figure 7A. *Results of the dye penetration test after TCML for ceramic inlays (CI) at the ceramic/luting agent (C/LA), enamel/luting agent (E/LA) and dentin/luting agent (D/LA) interfaces for Groups 1 (1.0 mm) and 2 (2.0 mm) and vestibular (non-functional), oral (functional) and proximal locations (median of maxima and 25–75% quartiles).*

The results of dye penetration for partial ceramic crowns (PCC) are summarized in Figure 7B and Table 3. For the experimental group "remaining cusp wall thickness" (1.0 mm and 2.0 mm), ERM and single pairwise comparisons showed no statistically significant difference in dye penetration. However, Group 2 (48.9%) showed a tendency towards less dye penetration at the dentin/LA interface than Group 1 (58.6%). For the experimental group "location" (oral and vestibular cusp), ERM and single pairwise comparisons showed no statistically significant difference in dye penetra-

Table 2: *Results of the dye penetration test for ceramic inlays (CI) at the ceramic/luting agent (C/LA), enamel/luting agent (D/LA) and dentin/luting agent (D/LA) interfaces for Groups 1 (1.0 mm) and 2 (2.0 mm) and vestibular (non-functional), oral (functional) and proximal locations (median of maxima and 25–75% quartiles).*

| | vestibular cusp | | | oral cusp | | | proximal | | | vestibular cusp | | | oral cusp | | | proximal | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Group 1 (1.0 mm) | | | | | | | | | Group 2 (2.0 mm) | | | | | | | | |
| | 25% | Med | 75% | 25% | Med | 75% | 25% | Med | 75% | 25% | Med | 75% | 25% | Med | 75% | 25% | Med | 75% |
| (C/LA) | 0.5 | 3.7 | 8.7 | 1.3 | 4.0 | 14.9 | 11.3 | 17.4 | 61.0 | 2.6 | 3.3 | 5.8 | 5.3 | 18.0 | 29.9 | 7.8 | 42.1 | 60.4 |
| (E/LA) | 2.9 | 13.2 | 30.1 | 19.4 | 23.4 | 29.5 | | | | 12.9 | 22.5 | 27.5 | 15.7 | 25.2 | 33.2 | | | |
| (D/LA) | | | | | | | 68.8 | 100 | 100 | | | | | | | 35.6 | 56.4 | 100 |

tion. For the experimental group "interface" (ceramic-, enamel- and dentin-LA), there was a significant difference (ERM) among the interfaces for ceramic-, enamel- and dentin-LA. Ceramic- (3.8-14.4%) and enamel/LA interfaces (13.6-24.4%) revealed significantly less dye penetration than the dentin/LA interface (48.9-58.6%), which was supported by single pairwise comparisons; for example, dye penetration at the proximal margin of Group 1 was statistically significantly higher ($p$=0.025) at the dentin/LA interface (58.6%) than at the ceramic/LA interface (11.8%).

For the experimental group "cavity design" (CI and PCC), in general, ERM showed no statistically significant influence of the remaining cusp wall thickness and location upon dye penetration data of the cavity design (CI and PCC). However, single pairwise comparisons revealed that PCC (58.6%) of Group 1 had statistically significantly less proximal dye penetration than CI (100%) at the dentin/LA interface ($p$=0.045).

**SEM Evaluation**

The results of the SEM evaluation for ceramic inlays (CI) are summarized in Table 4 and Figure 8A, as defined by the parameter "Compromised Adaptation" (CA). For the experimental group "remaining cusp wall thickness" (1.0 mm and 2.0 mm) and "location" (oral and vestibular cusp), ERM and single pairwise comparisons showed no statistically significant differences before and after TCML. The experimental group "interface" (ceramic-, enamel- and dentin-LA) showed statistically significant differences (ERM) among interfaces (ceramic-, enamel- and dentin-LA). Ceramic- (12.7-38.0%) and enamel/LA interfaces (13.0-32.6%) revealed less of a statistical significance of CA values than the dentin/LA interface (43.3-60.2%). However, the ERM and single pairwise comparisons for the experimental group "TCML" showed no influence, instead, it showed a tendency for less CA values before TCML.

The CA results for partial ceramic crowns (PCC) are summarized in Table 5 and Figure 8B. For the experimental groups "remaining cusp wall thickness" (1.0 mm and 2.0 mm) and "location" (oral and vestibular cusp), ERM and single pairwise comparisons showed no statistically significant difference before and after TCML. However, the experimental group "interface" (ceramic-, enamel- and dentin-LA) showed statistically significant differences. Ceramic (6.6-20.9%) and enamel/LA interfaces (7.3-17.4%) revealed statistically significantly less CA than the dentin/LA interface (22.2-48.9%). Furthermore, no influence of TCML was found for the

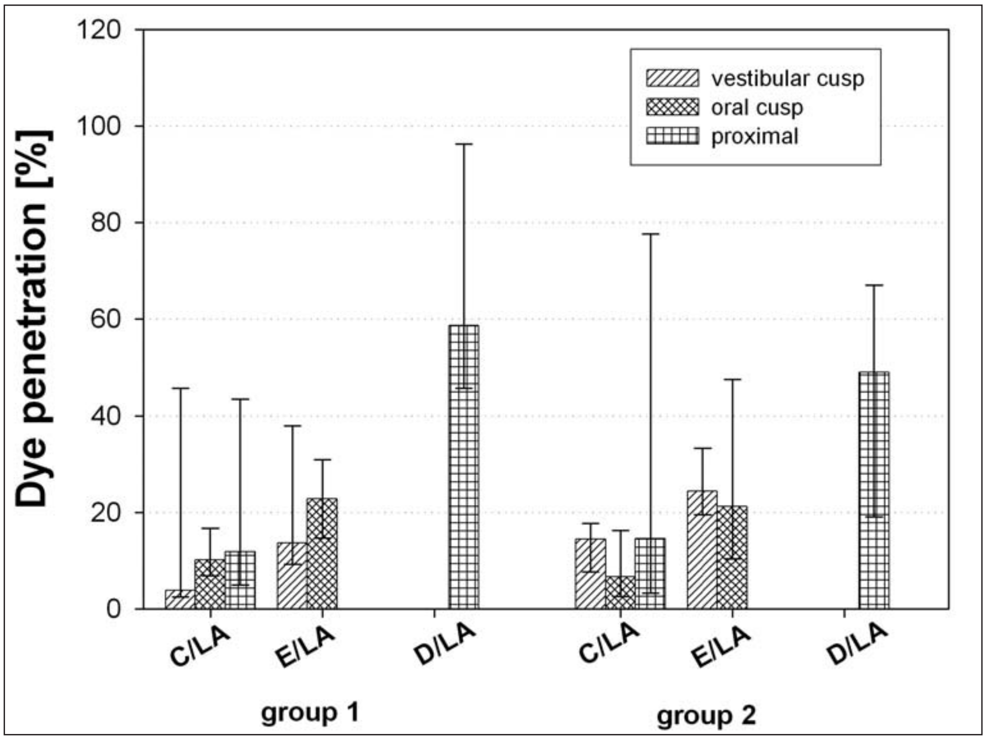


Figure 7B. *Results of the dye penetration test after TCML for partial ceramic crowns (PCC) at the ceramic/luting agent (C/LA), enamel/luting agent (E/LA) and dentin/luting agent (D/LA) interfaces for Groups 1 (1.0 mm) and 2 (2.0 mm) and vestibular (non-functional), oral (functional) and proximal locations (median of maxima and 25–75% quartiles).*

Table 3: *Results of the dye penetration test for partial ceramic crowns (PCC) at the ceramic/luting agent (C/LA), enamel/luting agent (D/LA) and dentin/luting agent (D/LA) interfaces for groups 1 (1.0 mm) and 2 (2.0 mm) and vestibular (non-functional), oral (functional) and proximal locations (median of maxima and 25–75% quartiles).*

| | vestibular cusp | | | oral cusp | | | proximal | | | vestibular cusp | | | oral cusp | | | proximal | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Group 1 (1.0 mm) | | | | | | | | | Group 2 (2.0 mm) | | | | | | | | |
| | 25% | Med | 75% | 25% | Med | 75% | 25% | Med | 75% | 25% | Med | 75% | 25% | Med | 75% | 25% | Med | 75% |
| (C/LA) | 2.5 | 3.8 | 45.7 | 6.9 | 10.1 | 16.7 | 4.9 | 11.8 | 43.5 | 7.7 | 14.4 | 17.7 | 2.6 | 6.7 | 16.2 | 3.3 | 14.5 | 77.6 |
| (E/LA) | 9.2 | 13.6 | 38.0 | 14.7 | 22.8 | 30.9 | | | | 19.5 | 24.4 | 33.3 | 10.4 | 21.2 | 47.4 | | | |
| (D/LA) | | | | | | | 45.7 | 58.6 | 96.2 | | | | | | | 19.1 | 48.9 | 67.0 |

Table 4: *Results of the compromised adaptation for ceramic inlays (CI) at the ceramic/luting agent (C/LA), enamel/luting agent (D/LA) and dentin/luting agent (D/LA) interfaces for groups 1 (1.0 mm) and 2 (2.0 mm) and vestibular (non-functional), oral (functional) and proximal locations before and after TCML, (median of maxima and 25–75% quartiles).*

| | vestibular cusp | | | oral cusp | | | proximal | | | vestibular cusp | | | oral cusp | | | proximal | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Group 1 (1.0 mm) | | | | | | | | | Group 2 (2.0 mm) | | | | | | | | |
| | Before TCML | | | | | | | | | Before TCML | | | | | | | | |
| | 25% | Med | 75% | 25% | Med | 75% | 25% | Med | 75% | 25% | Med | 75% | 25% | Med | 75% | 25% | Med | 75% |
| (C/LA) | 6.3 | 12.7 | 23.9 | 7.8 | 15.9 | 23.3 | 2.7 | 17.8 | 25.1 | 19.2 | 31.3 | 50.5 | 8.6 | 29.6 | 48.6 | 2.6 | 17.7 | 41.2 |
| (E/LA) | 3.9 | 13.0 | 19.3 | 8.0 | 13.5 | 31.3 | | | | 8.4 | 19.5 | 34.8 | 13.7 | 24.2 | 37.0 | | | |
| (D/LA) | | | | | | | 25.7 | 43.3 | 59.9 | | | | | | | 14.3 | 49.1 | 63.8 |
| | After TCML | | | | | | | | | After TCML | | | | | | | | |
| (C/LA) | 10.5 | 17.5 | 34.8 | 8.8 | 14.9 | 30.9 | 7.1 | 29.1 | 41.5 | 23.7 | 35.0 | 49.2 | 16.3 | 34.3 | 50.2 | 15.7 | 38.1 | 54.7 |
| (E/LA) | 4.7 | 15.6 | 29.2 | 11.7 | 21.9 | 42.1 | | | | 19.6 | 29.3 | 46.0 | 19.6 | 32.6 | 47.1 | | | |
| (D/LA) | | | | | | | 42.2 | 60.2 | 74.0 | | | | | | | 31.4 | 56.8 | 63.5 |

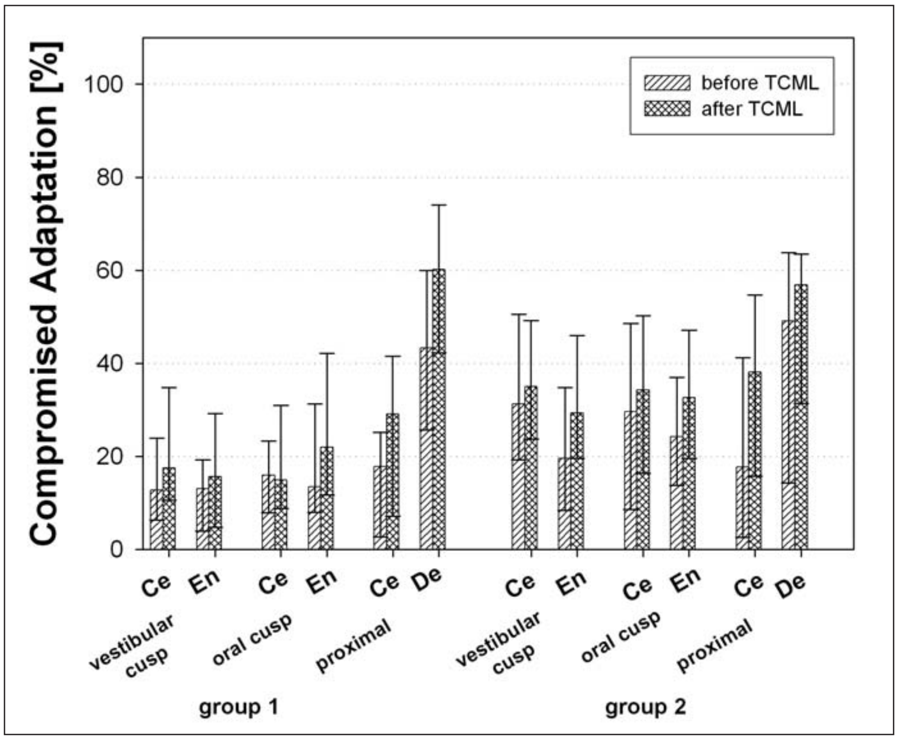


Figure 8A. *Compromised adaptation (MI plus GF and ME in percent) at the ceramic (Ce), enamel (En) and dentin (De) interfaces for ceramic inlays (CI) before and after TCML for Group 1 (1.0 mm) and Group 2 (2.0 mm) of vestibular (non-functional), oral (functional) and proximal locations (median of maxima and 25–75% quartiles).*

experimental group “time” (before and after TCML) using ERM and single pairwise comparison; instead, a tendency towards less CA values was found before TCML.

For the experimental group “cavity design,” ERM and single pairwise comparisons showed no statistically significant influence of the remaining cusp wall thickness and location upon ERM data of the cavity design (CI and PCC) before and after TCML. The CA values of PCC showed a tendency towards less CA than CI.

## Crack Formation

Examples of visible cracks of tooth substance before (BT) and after TCML (AT) are shown in Figures 4A and 4B. The crack lines running from the top of the non-functional cusp toward the cemen-to-enamel junction can be seen. The results of the crack evaluation are shown in Table 6. For the control group, no differences were observed in 11 cases before and after TCML. In one case, the number of cracks had increased.

Crack formation for CI: For the experimental group “remaining cusp wall thickness” (1.0 mm and 2.0 mm), no statistically significant differences at ΔAP (after preparation)/BT (before TCML) were found. Group 2 showed statistically significantly less change of crack formation ($\alpha$=0.004) than Group 1 at ΔBT/AT (after TCML). However, for the experimental group ”location” (oral and vestibular cusp), the ERM and Chi-Square tests revealed no statistically significant influence for crack formation at ΔAP/BT and ΔBT/AT. Furthermore, CI showed statistically significantly (ERM) less change in enamel crack formation at ΔAP/BT than at ΔBT/AT.

Crack formation of PCC: The experimental group “remaining cusp wall thickness” (1.0 mm and 2.0 mm) and “location” (oral and vestibular cusp) showed no statistically significant differences at ΔAP/BT and ΔBT/AT for a change in crack formation. However, Group 2 showed a tendency towards less change in crack formation than Group 1 at ΔBT/AT.

For the experimental group “cavity design” (CI and PCC), no statistically significant influence for change in crack formation was found.

Table 5: *Results of the compromised adaptation for partial ceramic crowns (PCC) at the ceramic/luting agent (C/LA), enamel/ luting agent (D/LA) and dentin/luting agent (D/LA) interfaces for Group 1 (1.0 mm) and 2 (2.0 mm) and vestibular (non-functional), oral (functional) and proximal locations before and after TCML, (median of maxima and 25–75% quartiles).*

| | vestibular cusp | | | oral cusp | | | proximal | | | vestibular cusp | | | oral cusp | | | proximal | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Group 1 (1.0 mm) | | | | | | | | | Group 2 (2.0 mm) | | | | | | | | |
| | Before TCML | | | | | | | | | Before TCML | | | | | | | | |
| | 25% | Med | 75% | 25% | Med | 75% | 25% | Med | 75% | 25% | Med | 75% | 25% | Med | 75% | 25% | Med | 75% |
| (C/LA) | 0.0 | 7.4 | 19.0 | 0.0 | 10.7 | 20.5 | 0.0 | 6.6 | 24.3 | 0.0 | 10.2 | 31.4 | 0.2 | 12.4 | 23.1 | 0.6 | 13.9 | 32.5 |
| (E/LA) | 0.0 | 7.3 | 18.2 | 0.0 | 7.8 | 28.5 | | | | 0.9 | 10.5 | 19.5 | 5.8 | 12.8 | 18.9 | | | |
| (D/LA) | | | | | | | 13.8 | 39.7 | 52.7 | | | | | | | 16.2 | 22.2 | 31.2 |
| | After TCML | | | | | | | | | After TCML | | | | | | | | |
| (C/LA) | 0.0 | 14.2 | 26.8 | 0.0 | 7.6 | 19.2 | 0.0 | 10.1 | 26.9 | 4.3 | 19.7 | 35.8 | 0.0 | 20.9 | 35.6 | 10.7 | 19.5 | 31.2 |
| (E/LA) | 4.3 | 12.0 | 20.7 | 0.0 | 10.0 | 21.8 | | | | 6.1 | 17.4 | 24.4 | 10.9 | 16.4 | 24.7 | | | |
| (D/LA) | | | | | | | 22.4 | 48.9 | 68.6 | | | | | | | 14.6 | 35.6 | 77.6 |

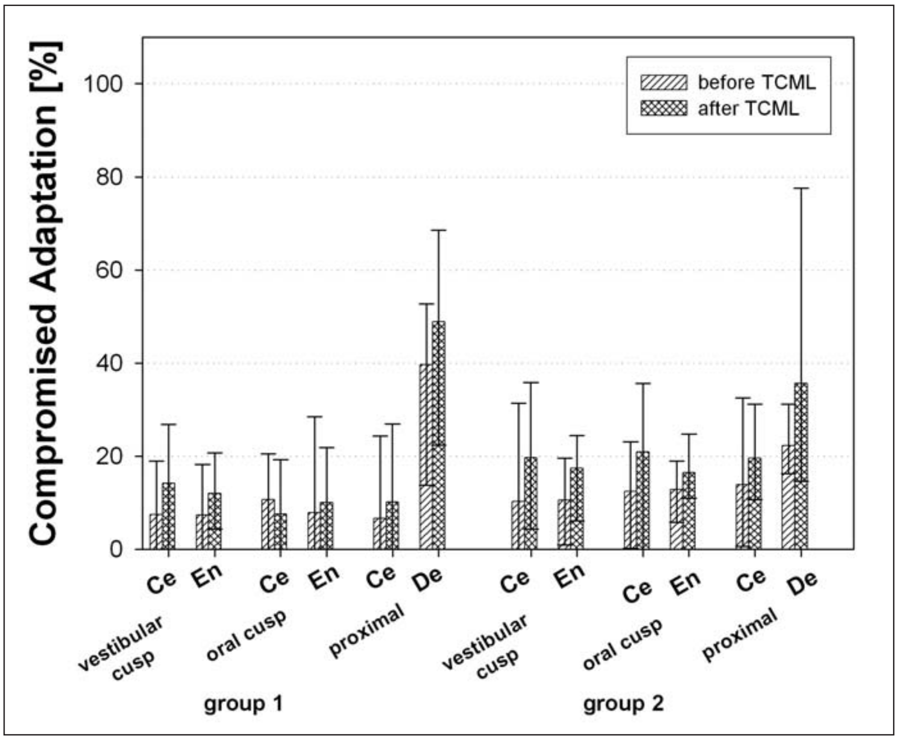


Figure 8B. *Compromised adaptation (MI plus GF and ME in percent) at the ceramic (Ce), enamel (En) and dentin (De) interfaces for partial ceramic crowns (PCC) before and after TCML for Group 1 (1.0 mm) and Group 2 (2.0 mm) of vestibular (non-functional), oral (functional) and proximal locations (median of maxima and 25–75% quartiles).*

## DISCUSSION

### Method

In the current study, the influence of four experimental conditions (remaining cusp wall thickness, location, cavity design and time) on two endpoints (marginal integrity and crack formation) was evaluated.

### Methods for Determining Marginal Integrity

Marginal integrity was evaluated using dye penetration and quantitative scanning electron microscopic (SEM) analysis, both of which are commonly applied methods to test the sealing of tooth-bonded restorations.[26-27] Microleakage, measured with dye penetration, is defined as the passage of bacteria, fluids or molecules between a cavity wall and restorative material.[28] SEM is a quantitative method that assesses the entire circumference of the tooth-restoration interface.[27] These methods examine different aspects of testing marginal adaptation. Dye penetration was used to evaluate a deficiency along the depth of a cavity, and SEM was used to determine the surface of the specimen.

TCML was used to simulate *in vivo* conditions. Krejci and Lutz[29] postulated that 120,000 *in vitro* loadings approximated six months of clinical use. The current study should thus simulate approximately 2–2.5 years of clinical use. However, a definite relationship between *in vitro* dye penetration and SEM data and the results from clinical (*in vivo*) testing still need to be established, with problems probably arising due to evaluation deficiencies for both the *in vitro* and *in vivo* methods. However, in the current study, dye penetration and SEM were used comparatively to identify risk factors for the *in vitro* crack formation of dental tissue when comparing the two different cusp wall thicknesses and cavity designs.

### Methods for Determining Crack Formation

In the current study, the appearance of visible cracks in the dental tissue was used as an early indicator of tooth fractures. However, clinical diagnosis may be very difficult, because, initially, the resulting cracks are incomplete and invisible in most cases and symptoms vary. To visualize the crack, some authors recommend staining the crack, applying transillumination or using an operating microscope.[30] In the current study, a reflective light microscope at 12x magnification was used to visualize and evaluate crack formation with differences detected between the experimental groups. All the specimens were evaluated by one person to establish comparability throughout the study.

**Marginal Integrity**

The marginal integrity (dye penetration and SEM analysis) of CI and PCC was basically shown to be independent of the remaining cusp wall thickness, location and cavity design. However, the proximal restoration margins within dentin revealed more distinct marginal deterioration when compared to enamel- and ceramic-LA interfaces. There is a statistically significant difference between Group 1 and Group 2 for CI. The data are in accordance with results reported in the literature for inlay[10] and onlay restorations.[31-32] Those authors reported that cervical restoration margins within dentin revealed significantly lower percentages of perfect margins than within enamel. Lang and others[33] found a time-dependent increase in marginal deterioration for large inlay restorations with proximal margins in dentin in a clinical investigation comparing extended ceramic inlay preparations with PCC. Those authors concluded that coverage of the weakened cusps, as performed in PCC restorations, resulted in indirect stressing of the tooth structure and reduced marginal deterioration of the adhesive bond.

**Crack Formation**

In the current study, no influence of location and cavity design on a change in crack formation was found, but the results show a definitive influence in the remaining cusp wall thickness on a change in crack formation for ceramic inlays after TCML compared to before TCML. As best recollected by the current authors, this is the first experimental indication for a clinical simulation experiment where a minimum remaining cusp wall thickness of at least 2.0 mm is necessary to prevent crack formation for all-ceramic restorations, especially CI.

In the literature, a number of recommendations on how to treat weakened teeth have been published. Haller and others[34] suggested cast gold onlays, adhesively bonded composites or ceramic inlays to reinforce dental tissues. Mehl and others[15] recommended the use of ceramic inlay restorations for extensive MOD cavities (2.4 mm residual walls) with proximal margins in dentin, while also recommending further clinical evaluation for restoring extremely extensive MOD cavities (1.3 mm residual walls). Apparently, even the cusp stabilizing effect of adhesive restorations[19-20] is limited to the number of cracks increasing at the critical wall thickness, thus increasing the risk of tooth fractures.

## CONCLUSIONS

Within the limitations of the current study, the remaining wall thickness of non-functional cusps of adhesively bonded ceramic restorations, especially ceramic inlays, should have at least a thickness of 2.0 mm to prevent crack formation, which, in the long run, may avoid tooth fracture. Furthermore, a remaining cusp wall thickness of 2.0 mm may reduce marginal deficiency (especially for CI) at the dentin/LA interface.

**Acknowledgements**

The authors express their thanks and appreciation to Jeremy Matis, Indianapolis, IN, USA, for his constructive criticism and advice regarding the manuscript.

*(Received 10 March 2008)*

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