Crack propensity of porcelain laminate veneers: A simulated operatory evaluation

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Statement of problem. Anterior teeth are especially subject to the thermal variations of ingested food and drinks. Postoperative cracks of porcelain laminates are considered a possible consequence of polymerization shrinkage, function, and thermocycling.
Purpose. This investigation was conducted to define the parameters associated with the development of cracks in porcelain veneers using cyclic thermal fatigue.
Material and methods. Twenty-seven maxillary incisors were restored with porcelain laminate veneers and subjected to thermocycling (5°C to 50°C) for 1000 cycles. Ceramic cracks were reported for 11 of the 27 specimens. Teeth were sectioned and prepared for SEM analysis. Measurements of the ceramic and the luting composite thicknesses were performed for each specimen at different restoration locations (facial, incisal, and proximal).
Results. No significant differences in the ceramic or the luting composite thicknesses were observed between cracked and uncracked specimens. However, significant differences were observed in the ratio of the ceramic and luting composite thicknesses. Most cracked samples exhibited a ratio at the facial location below 3.0 (2.6 ± 0.35), whereas most noncracked specimens were above this value (3.9 ± 0.19). Incisal and especially proximal measurements alone were not significantly different between cracked versus uncracked specimens. Ceramic was slightly thinner in the facial aspect than in the proximal aspect, which was also thinner than the incisal aspect. Composite in the facial aspect was thinner in the cervical area than in the incisal third of the tooth.
Conclusions. Significant cyclic temperature changes can induce the development of flaws in porcelain veneers. Control of tooth reduction and the application of die spacers during laboratory procedures undoubtedly represent key elements; a sufficient and even thickness of ceramic combined with a minimal thickness of luting composite will provide the restoration with a favorable configuration with regard to crack propensity, namely, a ceramic and luting composite thickness ratio above 3. (J Prosthet Dent 1999;81:327-34.)

CLINICAL IMPLICATIONS

This study points out the importance of a controlled and uniform tooth reduction. A minimal and homogeneous thickness of ceramic will provide the restoration with a favorable configuration (high CER/CPR ratio). For worn-down enamel surfaces, it is essential to reestablish the original volume of the tooth. The use of an additive diagnostic wax-up and corresponding silicon matrices are imperative in this regard. However, it is essential to obtain a good fit of the restoration, especially at the facial axial level of the preparation, which often presents the lowest ceramic thickness. During laboratory procedures, the die spacer should be carefully applied to avoid an excessive luting composite thickness at this particular location. The improved quality of both preparations (smooth contours, absence of undercuts) and final impressions will significantly facilitate the work of the ceramist, leading to minimal use of the die spacer.

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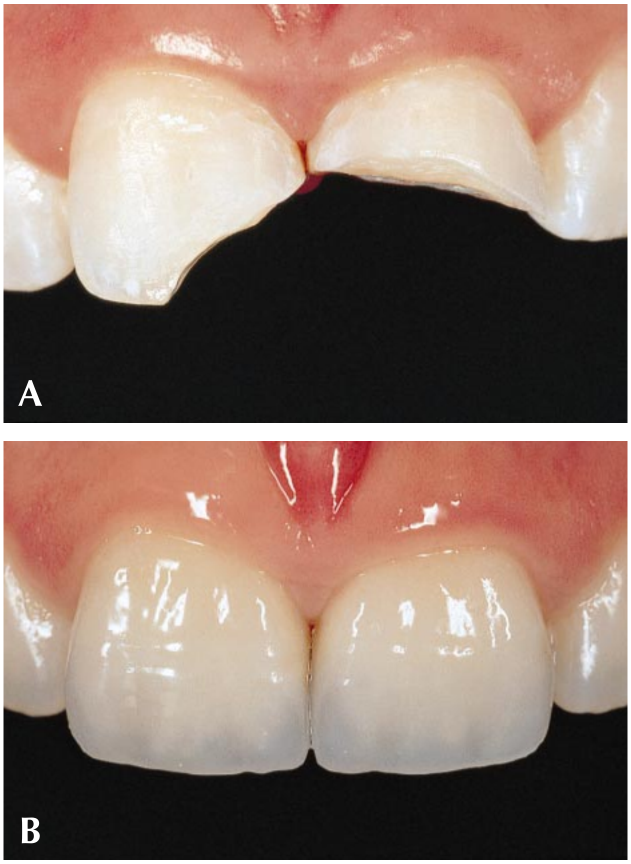

Fig. 1. A, Traumatic injury without pulp exposure. This patient represents one end of spectrum in which veneer restorations may be used. **B,** Bonded porcelain laminates allowed preservation of tooth vitality and respect for surrounding soft tissues (immediate postoperative view, now more than 4 years in service).

Bonding of facial veneers has been performed for more than 10 years and has become a useful and recognized technique.[1-3] Clinical evaluations[4-6] have demonstrated the excellent performance of such restorations in terms of fracture rates, microleakage, debonding, and periodontal response. Advantages of porcelain laminates are numerous and result from the combined advantages of composites (adhesion, economy of tooth substrate) and ceramics (color stability, wear resistance, enamel-like thermal expansion, and refined esthetics). Initially used to treat tooth discolorations of various kinds, laminate veneers have been increasingly replaced in those roles by more conservative therapeutic modalities such as chemical bleaching and microabrasion. However, this evolution has not led to a decrease of indications for ceramic laminate veneers, as others have been recently added,[7] as an answer to the primary requirements of conservative dentistry: preservation of tooth substance and safeguarding of tooth vitality (Fig. 1).

However, practitioners are prudent when considering such treatment modalities, because ceramics remain brittle materials. Incisal chipping[8] and the development of flaws[9] represent the most common clinical failures of porcelain laminates. In vitro simulated impact,[10] load to failure,[11,12] and photoelasticity studies[13] have demonstrated the ability of porcelain veneers to restore and even exceed the strength of the natural tooth. However, additional scientific data are required to address the parameters related to the crack propensity of the restoration. Ceramic flaws may occur before and during luting procedures, depending on the ability of the operator to carefully handle the restoration. Unfortunately, postoperative cracks are also reported by practitioners as a possible consequence of polymerization shrinkage, function, and thermocycling. In this regard, one may question the potential influences of newer preparation designs extending into the proximal area[14] ("wrap around"), the location and configuration of the margins, and the relative thickness of the luting material and the ceramic. A major consideration that should not be neglected is the thermal variations of ingested food and drinks that affect anterior teeth. Temperature ranges in the oral environment may vary between 0°C and 67°C,[15] and it is assumed that the thermal expansion mismatch between tooth and restorative materials can create significant stresses in the porcelain.

The purpose of this study was to define the parameters responsible for the development of cracks in porcelain veneers. Special attention was given to the experimental method to simulate clinical conditions during each step of the restorative procedure, including operator and patient environment, bone, and soft tissue reproduction. This accounts for the description of this study as a "simulated operatory evaluation." SIM-OPS (simulated operatories) are common ways of assessing practical difficulties in the clinical use of dental materials.

METHOD AND MATERIAL

Eighty-one recently extracted incisors were collected, scaled, cleaned with pumice, and stored in physiologic saline solution and 0.2% azide. Teeth were placed in groups of 3 and mounted in a simulation model that exhibited an artificial periodontal support (acrylic resin bone and a soft silicone gingiva up to the level of the cementoenamel junction) (Fig. 2). Twenty-seven models were fabricated. Each model was then placed in an artificial patient/operatory environment (DSE EWL 5180, D-7970, KaVo, Leutkirch, Germany). Twenty-seven clinicians were asked to make 1 standardized preparation at 0.5 to 0.7 mm uniform reduction with diamond burs (Geneva Prep Set, Intensiv, Viganello, Switzerland) and silicone guides, in accordance with the recommendations of a written protocol. Only the

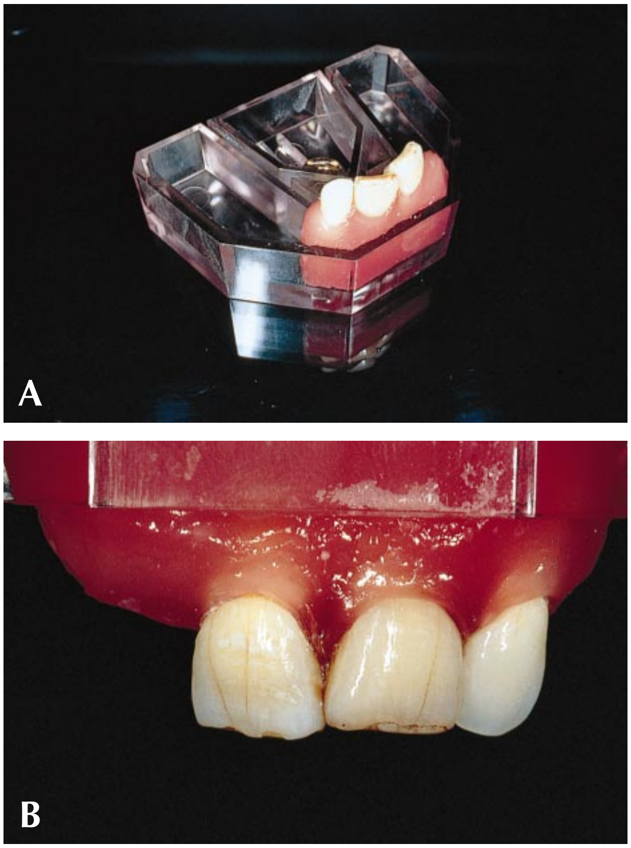

Fig. 2. One simulation model used for this study. **A,** Roots are embedded in resin reproducing bone (not visible). **B,** Anatomic crowns are surrounded by artificial soft tissues made of silicon material.

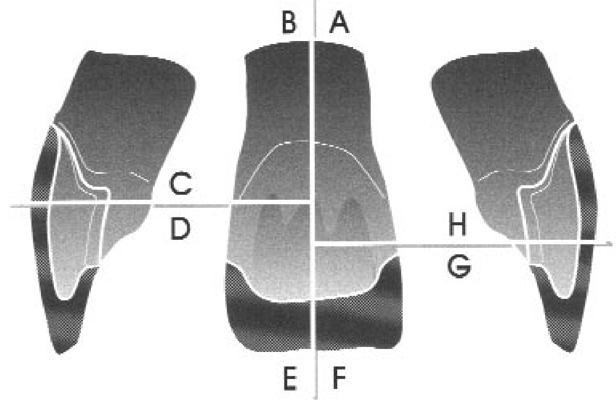

Fig. 3. Schematic representation of section types and sectioned surface labels (*A* to *H*).

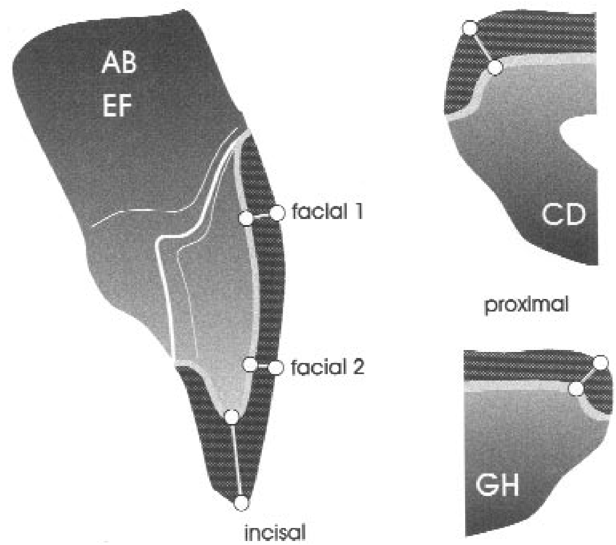

Fig. 4. Schematic representation of sectioned surfaces and locations of measurements (facial 1, facial 2, incisal, and proximal).

central tooth was prepared to exhibit good simulation of the clinical situation, namely, the presence of intact neighboring teeth.

Before tooth preparation, preexisting restorations and decay were eliminated and the cavities were restored with direct adhesive fillings. Teeth were maintained in a wet environment by using a water spray during the entire preparation steps. After preparations were completed and supervised, impressions were made with a polyether material (Permadyne, ESPE, Seefeld, Germany) and poured in a vacuum-mixed improved stone (GC Fujirock EP, GC Corp, Leuven, Belgium).

The ceramic laminates were fabricated with a refractory die technique (Ducera-Lay refractory die material, Duceram, Rosbach, Germany) and a feldspathic porcelain (Creation, Klema, Meiningen, Austria). The die spacer consisted of a wax (Fixierwachs, Bredent, Senden, Germany) applied to the original stone die with a hot electric spatula to form a thin film 1 mm short of the margin. Each veneer was fabricated by a different dental technician, and then the veneers were tried on the teeth. Finally, traditional luting procedures were performed, including rubber-dam insulation. The inner surface of the restoration was etched for 90 seconds with 10% ammonium bifluoride gel (Biodent Retentionsgel, Dentsply/DeTrey). After abundant rinsing and drying, the same surface was coated with silane (Biodent Coupling Agent 90, Dentsply/DeTrey) and the veneer was heat treated for 5 minutes at 100°C according to the instructions of the silane manufacturer.

After etching the enamel (Ultretch, Ultradent), use of a dentin adhesive (Optibond, Kerr) and a photopolymerizing composite (Herculite Incisal LT, Kerr), the restorations were seated with finger pressure. Excess luting material was removed, and then the margins were covered with a glycerin jelly. The polymerization tip was applied intermittently for 120 seconds

Table I. CER/CPR ratio

Data grouping	I Facial 1,2	II Facial 1,2 + proximal	III Facial 1,2 + incisal	IV Proximal + incisal
Number of teeth in the subset (no. cracked/not cracked)	26 (11/15)	25 (10/15)	18 (7/11)	17 (6/11)
Cracked vs not cracked	*P*=.002* cracked < not cracked	*P*=.08	*P*=.013 cracked < not cracked	*P*=.36
Within-tooth location	*P*<.001* facial 2 < facial 1	*P*<.001* facial 2 < facial 1 < proximal	*P*<.001* facial 2 < facial 1 < incisal	*P*=.56

**P* value below the Bonferroni significance threshold (.0125).

Table II. CER thickness

Data grouping	I Facial 1,2	II Facial 1,2 + proximal	III Facial 1,2 + incisal	IV Proximal + incisal
Number of teeth in the subset (no. cracked/not cracked)	26 (11/15)	25 (10/15)	18 (7/11)	17 (6/11)
Cracked vs not cracked	*P*=.016	*P*=.22	*P*=.068	*P*=.11
Within-tooth location	*P*=.18	*P*<.001* facial 1,2 < proximal	*P*<.001* facial 1,2 < incisal	*P*<.001* proximal <incisal

**P* value below the Bonferroni significance threshold (.0125).

Table III. CPR thickness

Data grouping	I Facial 1,2	II Facial 1,2 + proximal	III Facial 1,2 + incisal	IV Proximal + incisal
Number of teeth in the subset (no. cracked/not cracked)	27 (11/16)	26 (10/16)	25 (10/15)	24 (9/15)
Cracked vs not cracked	*P*=.15	*P*=.50	*P*=.12	*P*=.93
Within-tooth location	*P*=.001* facial 1 < facial 2	*P*<.001* facial 1, proximal < facial 2	*P*=.37	*P*=.36

**P* value below the Bonferroni significance threshold (.0125).

on each side of the tooth (palatal and facial). Margins were then finished with a scalpel and carbide finishing burs for the removal of excess resin. Neither dentists nor dental technicians had special training in the field of porcelain laminates.

After the finishing procedures were completed, the teeth were stored in saline solution and 0.2% sodium azide for 21 days at 37°C, followed by transillumination with an optical fiber for the detection of cracks in the porcelain. Specimens were thermocycled 1000 times, between 5°C and 50°C, with a 30-second dwell time at each temperature. Additional crack detection was performed. Specimens were subjected to dye infiltration test by immersion of the restored crown into a 0.5% cresyl blue solution for the final display of cracks in the porcelain. Each specimen was photographed on its facial and palatal aspects at 3× magnification (Nikon camera system, Nikon Inc, Nikon, Japan). Specimens were finally embedded in a clear epoxy resin (Epofix, Struers). Each specimen was sectioned incisogingivally in the center of the tooth and mesiodistally (Fig. 3), with a low-speed diamond saw (Isomet, Buehler Ltd, Lake Bluff, Ill.). The sectioned surfaces were immediately cleaned with an air-abrasion system, etched for 15 seconds with H_3PO_4 37%, and replicated with polyvinyl siloxane (Extrude, Kerr Mfg Co, Orange, Calif.) for the fabrication of gold-plated resin specimens.

Gold-plated replicas were analyzed under SEM to quantify the thickness of the ceramic (CER) and the luting composite (CPR) at 5 levels of the restoration (Fig. 4): facial 1, facial 2, incisal, proximal mesial, and distal (interdental crest area). Special attention was given to the configuration of the restorations; therefore the ratio between ceramic/luting composite thicknesses (R = CER/CPR) was calculated from measurements made along the facial axial wall and in the interdental crest area. Each measurement was performed on both sectioned surfaces.

Statistical analysis

The CER/CPR ratio and the thicknesses of CER and CPR were calculated with a “between- and within-sub-

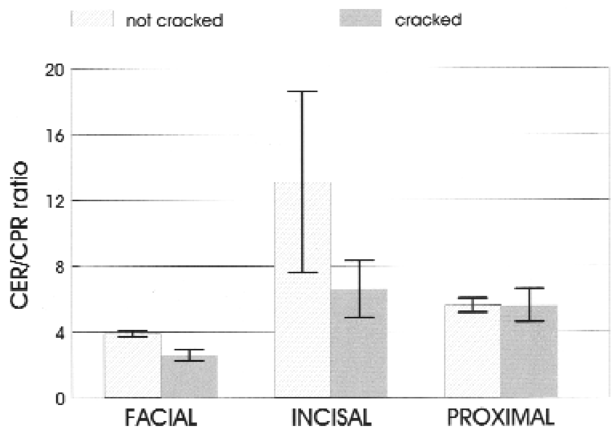

Fig. 5. Mean values (±SD) of log (CER/CPR) ratio.

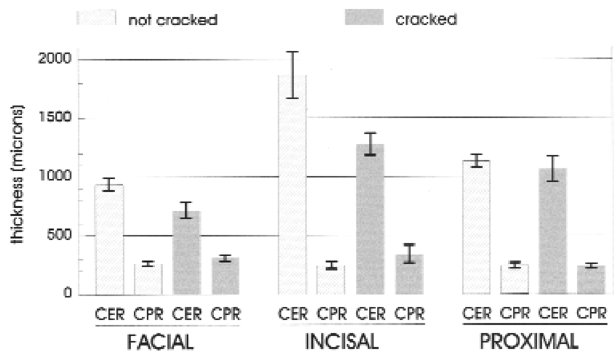

Fig. 6. Mean values (±SD) of ceramic (CER) and luting composite thicknesses (CPR).

jects" analysis of variance (ANOVA), in which: subjects were teeth; the between-tooth factor was the presence or absence of cracks in the ceramic; and within-tooth factor was the location (facial vs incisal vs proximal).

Raw-scale measurements of CER and CPR thicknesses and the common logarithm of the CER/CPR ratio were analyzed. The log-transform was used to homogenize the variance and to make the analyzed measurements more normally distributed. Each parameter was explored by using 4 groupings of the data: (I) facial 1,2 alone; (II) facial 1,2 along with proximal measurements; (III) facial 1,2 along with the incisal measurement; and (IV) proximal measurements along with the incisal measurement.

Sections were grouped because of missing measurements of ceramic thickness on the incisal section for several teeth and a few missing measurements of composite thickness. Given the pattern in which the data were missing (most of the missing data are incisal measurements), analyses that used all the data would run a noteworthy risk of spurious findings. Therefore only teeth with complete measurements were analyzed, and the 4 groupings were analyzed separately. As Tables I through III indicate, analyzing all groupings at once would sacrifice about one third of the available data for analyzing the facial and proximal sections. To compensate for these repeated analyses, a significance threshold *P* of .0125, which corresponds to a Bonferroni correction an overall alpha (type I error) of .05 across 4 analyses, was used for each grouping.

RESULTS

The log (CER/CPR) ratio, the ceramic thickness, and the luting composite thickness are illustrated in Figures 5 and 6 and presented in Tables I through III. For cracked specimens, no ceramic flaws were present after the 21-day storage in saline; all were present after the cyclic thermal test.

CER/CPR ratio

The CER/CPR ratio indicated some differences between cracked and noncracked teeth (Fig. 5 and Table I). Differences between cracked and noncracked teeth were significant for facial measurements considered alone (group I). For facial measurements, along with incisal measurements (group III), the *P* value for the difference was just greater than the threshold of significance; including the incisal measurements reduced the average difference between cracked and noncracked teeth. Similarly, when proximal measurements were included with facial measurements (group II), the difference between cracked and noncracked teeth was still less impressive (P=.08); inclusion of the proximal measurements also reduced the average difference between cracked and noncracked teeth. Moreover, the section-by-crack interaction was significant (P=.01), reinforcing the impression that the average log (CER/CPR) ratio was not the same for the facial measurements and the proximal measurements. Finally, a nonsignificant result for incisal and proximal teeth (group IV) indicated that the ratio did not differ between cracked and noncracked teeth for proximal measurements.

The facial CER/CPR ratio was 3.9 ± 0.19 for noncracked specimens and 2.6 ± 0.35 for cracked specimens; mean and standard deviation were computed on the raw scale. The facial CER/CPR ratio was above 3.0 for 14 of the 16 noncracked specimens, and it was below 3.0 for 9 of the 11 cracked specimens. Figure 7, *A* through *C*, illustrates this with a macrophotograph and SEM views of a typical, cracked specimen. Significant differences also appeared between sections. The ratio was significantly lower for facial 2 compared with facial 1, which in turn was significantly lower than incisal and proximal.

Thicknesses of ceramic and composite

Ceramic and composite thickness did not differ between cracked and noncracked teeth. However, for

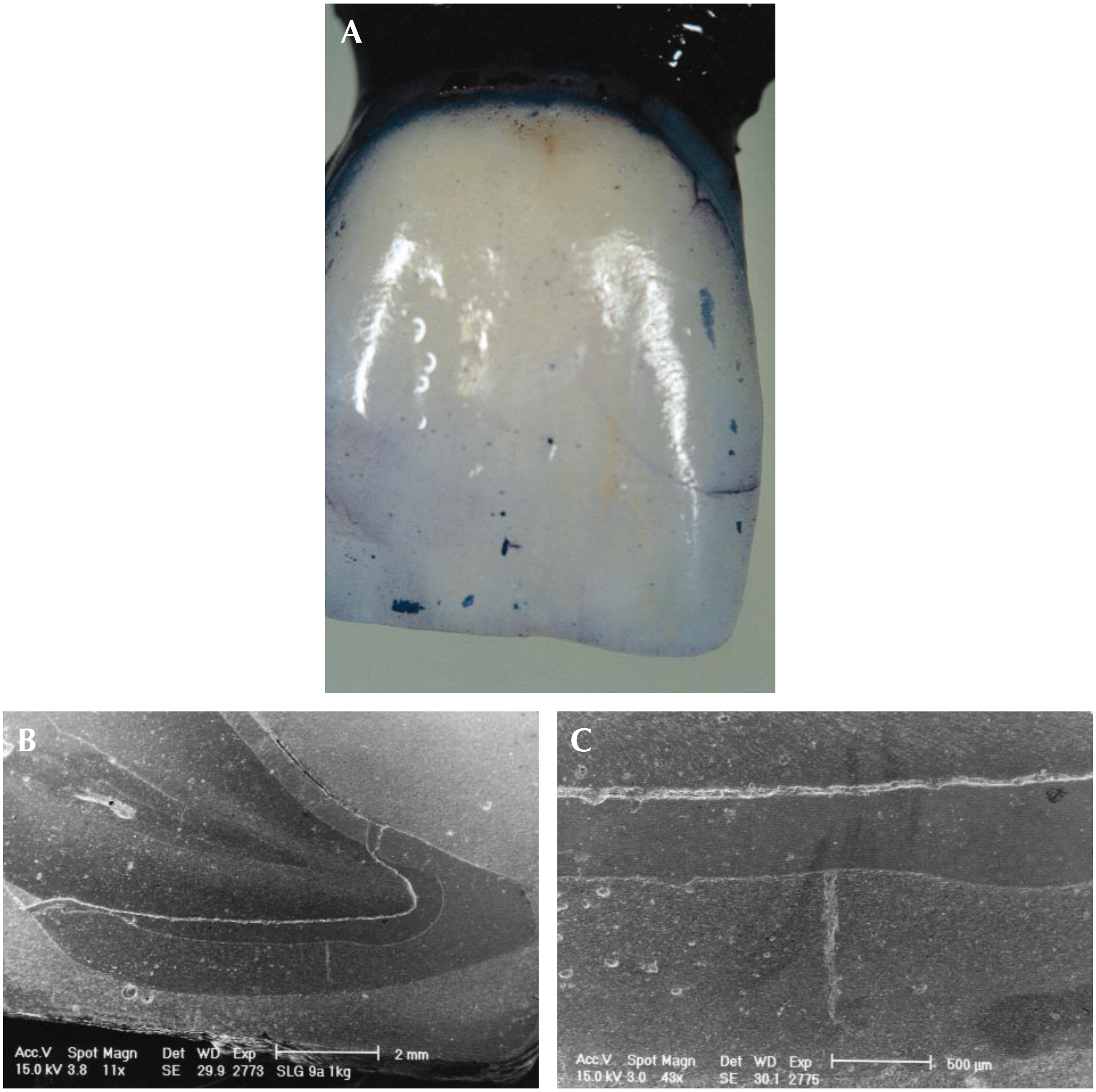

Fig. 7. Typical aspects of cracked specimen. **A,** Macrophotograph of cracked sample (original magnification, ×3). Facial surface exhibits multiple cracks in ceramic restoration. **B,** Indirect SEM observation of B-E sample section (original magnification, ×11). Flaw is visible on facial aspect and on palatal surface near margin. Extensive dentin exposure showed in this section is not representative because lateral extensions of tooth involved mostly enamel. **C,** Detailed SEM microphotograph of interface and flaw (original magnification, ×43) demonstrates adverse facial CER/CPR ratio (R = 2.35).

ceramic thickness, facial values (group I) came close to the threshold for significance, with cracked specimens demonstrating a trend toward thinner facial ceramic (936 ± 53 for noncracked vs 715 ± 67 for cracked). For composite thickness, facial values (group I) also revealed a nonsignificant trend with cracked specimens thicker than noncracked specimens (262 ± 19 noncracked vs 310 ± 26 cracked). The presence of these 2 nonsignificant trends is consistent with the results for the log (CER/CPR) ratio, discussed previously, in which cracked teeth had lower ratios than noncracked teeth.

Significant differences were evident between sections. The facial ceramic was thinner than the proximal, which in turn was thinner than the incisal. Few statistically significant differences were found in the composite thickness. The facial composite was thinner in the cervical area when compared with the incisal third of the tooth.

DISCUSSION

It is a challenge to study the occurrence of cracks in a complex structure such as porcelain laminate because of the presence of many interacting variables. Some researchers have assumed that the structural performance of brittle dental materials cannot be directly correlated to their strength values.[16] Standard ceramic properties (flexural strength, fracture toughness) therefore may not be sufficient to describe the occurrence of flaws in a clinical situation. Consequently, the term "crack propensity" has been used to characterize the structural performance of the global restorative system instead of specific material properties.

The precise origin of spontaneous post-bonding cracks has not yet been elucidated. It was mandatory to find an experimental design able to (1) allow different possible causes to be isolated and (2) reproduce this kind of failure. Possible causes were obtained by variations in the restorations through the wide range of CER and CPR thicknesses (each sample being performed by a different operator, either dentist or technician). Among available experimental designs, load-to-failure experiments are appropriate for exploring the total fracture behavior but are difficult to control in the early stage of crack formation. Cyclic mechanical loading combined with thermocycling would definitely represent the best experimental design to create ceramic cracks. Such a situation was indirectly reproduced in the simple design of our study. It seems reasonable to assume that thermal variations generated such a cyclic mechanical load that resulted from differential thermal expansion of the luting composite (in the range of $30/°C \times 10^{-6}$)[17] when compared with the traditional feldspathic porcelain ($13.5/°C \times 10^{-6}$).

The laminate seemed to act as a rigid shell (high E-modulus), which restrained the dimensional change of the underlying composite. In our study, neither the low E-modulus of the composite nor the elasticity of underlying tissues were sufficient to overcome the repeated stresses produced by the dimensional changes of the luting material. Damage to the porcelain was most extensive when the facial CER/CPR was small, namely, the force of the dimensionally changing cement was large relative to the thickness and, thus, the strength of the ceramic. Ceramic cracks were not found after the 21-day storage in saline but only after the thermocycling. Accordingly, the static stress produced by the shrinkage of the luting composite was not directly related to the development of flaws, but its combination with the repeated thermal loads may have played a key role, considering that feldspathic porcelains demonstrate cumulative damage with cyclic mechanical fatigue.[18]

Our study demonstrated that the CER/CPR ratio gave the greatest power to distinguish cracked laminates from noncracked laminates. Tendencies that were not significant in CER and CPR values considered alone were revealed by the combination of both parameters in the form of their ratio. This may be also explained by the fact that the CER/CPR ratio was relatively independent of the absolute values of CER or CPR individually, which themselves are dependent on the plane of sectioning. Similar reasoning applies to the eventuality that the section may not be exactly perpendicular to the SEM beam. Different measurement locations had different power levels to distinguish between cracked and noncracked laminates. Significant differences were found for facial values (group I). As previously noted, the CER/CPR ratio revealed this difference, capturing the simultaneous tendencies in the thickness of the ceramic and the luting composite (Tables II and III). Practically, the composite thickness may be influenced by the application of the die spacer during laboratory procedures and by eventual incomplete seating of the restoration. Both parameters are closely related because the seating of laboratory-made restorations may be affected when the die spacer is omitted.[19,20] However, an excessive layer of die spacer can also generate an enlarged luting space,[21,22] which compromises the space left for the ceramic.

Ceramic thickness values did not discriminate between cracked and noncracked specimens, but just indicated that overall thicknesses were larger at the incisal edge and at the proximal crest. This may be logically explained by the structure of the laminate, which tends to restore incisal length and emphasizes the 3-dimensional volume of the facial aspect of teeth, of which the thickness of the interdental crest represents a key element in this regard. The higher standard error observed in the incisal thickness of the specimen is explained by the fact that no special instructions were given to the dental technicians to define the incisal length. The development of flaws was influenced more by the facial thickness of the ceramic than by the incisal length, and the CER/CPR ratio measured either in the incisal or the proximal area did not play a major role in the ceramic crack propensity.

CONCLUSIONS

Within the limits of this study, the following conclusions were drawn:

1. Significant differences were observed for the ratio of the measurements of the ceramic and luting composite thickness (CER/CPR) values for each location. Most cracked specimens exhibited a facial ratio below 3.0, whereas most noncracked specimens had a facial ratio above this value. Incisal and especially proximal measurements alone were not significantly different between cracked and noncracked specimens.

2. Neither the absolute ceramic (CER) nor luting composite thickness (CPR) values demonstrated any differences between cracked and noncracked specimens.

3. Overall ceramic thickness was significantly lower at the facial axial level when compared with incisal and proximal. The overall luting composite thickness was significantly lower in the facial cervical area when compared with the facial incisal third of the tooth.

4. Tooth reduction is important because a sufficient and homogeneous thickness of ceramic will provide the restoration with a favorable configuration, namely, a CER/CPR ratio above 3.0. Special attention in this matter appears to be required at the facial axial level of the preparation.

5. During laboratory procedures, the die spacer should be carefully applied to avoid an excessive luting composite thickness that would reduce the CER/CPR ratio.

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