The primary weakness of dental ceramics is their low resistance to tensile stress. Furthermore, brittleness is likely to be the most important clinical characteristic of ceramics, especially glass or feldspathic ceramics. Clinical failure rates of all-ceramic restorations in the dental literature confirm this weakness in comparison to metal ceramic restorations.1-10 Nevertheless, the esthetic and biologic advantages of all-ceramic restorations have led to many efforts to improve the mechanical properties of dental ceramics. Several strengthening techniques and principles were developed and investigated: modification of the material composition by thermal processing, dispersive strengthening, and guided mismatch of crystal and matrix components to create compressive prestressing forces or to interrupt crack propagation, eg, tempering, Al₂O₃ reinforcing, or ceramming of crystal particles.5-10 Other approaches include modifications of surface characteristics such as surface roughness by polishing, glazing, or etching,11-14 or varying the surface structure by ion exchange or coatings.15,16 The most successful technique has been to create metal ceramic compounds.17,18 Thus far only one ceramic-ceramic compound, the glass-infiltrated alumina core system In-Ceram (Vita Zahnfabrik, Bad Säckingen, Germany), has had clinical success.19,20 Clinical approaches to avoid fracture or failure of all-ceramic restorations include: specialized indications and rules and procedures including adhesive resin luting of all-ceramic restorations21-23 according to enamel and dentin conditioning techniques.24,25

There are two concepts behind the clinical use of adhesive techniques: (1) the more effective stress transfer by the creation of strong bonding forces at the enamel-resin-ceramic interfaces analogous to the principles of compound systems, and (2) the strengthening effects resulting from resin coatings following the principles of surface modification to inhibit crack initiation.14 Clinical results seem to confirm the validity of the adhesive compound system for inlay and veneer restorations,26 but are limited when applied to prosthodontic restorations. The indication of crowns is commonly related to the greater loss of dental hard tissues, especially enamel, as a result of tooth destruction or...
The present study was designed to evaluate the effects of different cementation modes on the fracture resistance of all-ceramic crowns. The questions addressed were:

1. Do different luting materials influence the fracture resistance of feldspathic ceramic crowns?
2. Do adhesive surface conditioning and the sealing of the crown inner surface with a resin bonding agent influence fracture resistance?
3. Does adhesive surface conditioning of the supporting die influence the fracture resistance of resin luted crowns?

The main outcome variable was the fracture resistance measured as the maximal fracture load by progressive incisal loading until catastrophic fracture.

**Materials and Methods**

In this in vitro study, 120 identically shaped Empress (Ivoclar, Schaan, Liechtenstein) crowns were subjected to a fracture test on steel dies. Twenty steel testing dies were produced by copying one original master die with the proportions of a maxillary central incisor. The simulated preparation had a 1-mm circumferential 90-degree finishing line with a rounded internal line angle. The cervical preparation line followed the assumed clinical contours of the marginal gingiva. The approximate height of the prepared axial walls was 5.2 mm with a mesiodistal diameter of 5 mm and a convergence angle of 6 degrees. Crowns were fabricated using the IPS Empress technique by replicating the form and dimension of one original crown. Six crowns were prepared from each testing die. The test crowns were divided into six groups. Replication was accomplished using reusable molds to obtain wax models of the original crown or resin models (GC Pattern Resin, GC International, Hofheim, Germany) of the original master die. The resin dies were invested and cast (Remanium CD, Dentaurum, Pforzheim, Germany). Each wax crown model was controlled and adapted at the margins on its related cast die, invested, heat pressed, and glazed according to the manufacturer's instructions. The crowns were arbitrarily assigned to six groups.

Each group of 20 crowns was assigned to one of the following cementation modes (Table 1): zinc phosphate cement (Phosphacap, Ivoclar) (A, B), glass-ionomer cement (Ketac Cem, ESPE, Seefeld, Germany) (C, D), and dual-polymerizing resin cement (DualGement, Ivoclar) (E, F). For groups B, D, E, and F, the inner surfaces of the crowns were conditioned by etching with hydrofluoric acid 5% (Ceramic Etching-gel, Ivoclar), coating with silane solution (Monobond-S, Ivoclar) for 30 seconds by using a small brush, and sealing with light-polymerizing resin bonding agent (Heliobond, Ivoclar). In the last group E, the prepared surfaces of the 20 testing dies were also conditioned using a two-phase metal surface coating system (Rocatec, ESPE) referred to as an effective metal-resin bonding system.

**Conditioning Procedures**

The inner surface of the crowns in groups B, D, E, and F was conditioned immediately prior to cementation: hydrofluoric acid etching for 60 seconds, the removal and rinsing with water spray for 60 seconds, and air drying for about 40 seconds. Silane was placed for 40 seconds before being air dried. The silanized surfaces were then coated with a thin layer of resin bonding agent, and the excess was removed using an air stream. The units were then light polymerized (Heliomat, Ivoclar). During prestudies no misfit resulting from the resin coating was detected using a stereomicroscope (magnification ×10).
The conditioning of the dies in group F required two steps of airborne particle abrading: 110-µm alumina grains to clean and roughen the surfaces (Rocatec Pre, ESPE), then silicate-covered alumina grains to implant reactive surface particles (Rocatec Plus, ESPE). The prepared surfaces were then coated with a silane coupling agent (Rocatec Sil). By using this design it was possible to test under practically reproducible conditions on reusable dies and with an effective stress transfer by simulating full-adhesive bonding between crown and supporting die structure. Both conditions could not be achieved by using natural teeth with respect to dimensions and bond strength.

**Cementation Procedures**

All crowns were luted to the dies under standardized conditions. The dies were mounted vertically. Encapsulated zinc phosphate cement (A, B) and glass-ionomer cement (C, D) were used. The resin luting material (E, F) was prepared in equal proportions and spatulated for 15 seconds. The crowns were completely filled with the luting agent and seated on the dies. An axial load of 28.7 N was then applied on the incisal edge for 15 minutes. The axial direction was provided by a rail cart with four precision bearing wheels carrying the weight. To avoid damage to the crowns by stress peaks, a silicone block (Optosil, Bayer Dental, Leverkusen, Germany) was positioned between cart and crowns during load application. Surplus liquid resin material was removed using a small brush, and the gap region was covered with glycerin gel (Air Block, DeTrey, Dreieich, Germany) to prevent oxygen inhibition. Light activation of the resin luted groups (E, E) was performed from four sides for 1 minute each after a loading time of 5 minutes. Excess cement was broken away or removed using a scalpel (Aesculap No. BB 542, Aesculap AG, Tuttlingen, Germany). No finishing was performed.

**Measurements**

After at least 48 hours of dry storage, each group of cemented crowns was subjected to breaking strength testing. The main outcome variable was the fracture resistance of the crowns measured by their maximal fracture load: A progressive load was applied incisally onto a 0.5-mm-thick tin foil under a load angle of 45 degrees. The load was measured until the ceramic crown failed by catastrophic fracture. The measurements were performed in a universal testing machine (Zwick 1454, Ulm, Germany) using a rounded bar, incisal loading points, and a cross-head speed of 0.5 mm per minute. The cemented crown specimens were mounted in a device to fix all dies identically at 45 degrees to the loading bar. The position of the device was marked on the table of the testing machine to be reproducible after changing the dies. A 0.5-mm sheet of tin foil was placed on the incisal edge to compensate any difference in the incisal loading points. Load “F₁” and way “s₁” of the loading bar were registered by the testing machine and were additionally controlled by computerized monitoring during measurement and graphed as $F₁ = f (s₁)$ on the monitor. The criterion for cessation of loading was the catastrophic fracture of the crown, which was automatically registered by the testing machine. The data sets were stored, and the maximum values were evaluated by listing all data.

**Statistical Evaluation**

A statistical comparison was made between the groups with respect to the distributions of the maximum fracture load. The normal distribution of the data sets was previously tested by using the Kolmogorov-Smirnov test.

The statistical analysis tested the following hypotheses:

- $H₀$: The tested groups were from the same population. Therefore, the cementation modes had no influence on the fracture resistance of ceramic crowns in vitro.
- $H₁$: The tested groups were not from the same population. Thus, the cementation modes yielded differences of the fracture resistance in vitro.

According to the purposes of the study, the following questions were addressed related to the statistical analysis:

1. Do different luting materials influence the fracture resistance of pressed all-ceramic crowns? This question was answered by testing groups A, C, and E using multiple comparisons.
2. Do adhesive surface conditioning and sealing with resin bonding agent of the crown inner surface influence the fracture resistance? This question was answered using pairwise testing of A and B and C and D.
3. Does adhesive surface conditioning of the supporting die influence the fracture resistance of resin luted crowns? To answer this question, the groups E and F were compared by pairwise testing.

The significance level was determined at $P < .01$. 

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Cementation Modes and Fracture Resistance of Crowns
Results

Six groups of 20 crowns were loaded until catastrophic failure occurred. Measurement $B_{12}$ was lost, leaving 119 data sets. The glass-ionomer luted crowns (C) had the lowest mean value of fracture load with 217 N ($\pm$ 38.0 N), followed by the group of conditioned glass-ionomer crowns (D) with 255 N ($\pm$ 73.1 N). The zinc phosphate cemented groups showed similar values: 294 N ($\pm$ 94.2 N) for A and even less for the previously conditioned crowns (B): 282 N ($\pm$ 59.4 N). The resin cemented crowns (E) showed increased values: 382 N ($\pm$ 46.1 N). The highest values were found with crowns resin cemented to conditioned dies (F): 688 N ($\pm$ 99.2 N). Medians, distributions, and the overall range of the results are illustrated in Fig 1. A close relationship between the conventionally luted crowns and their resin bonded correspondents A and B, and C and D, was obvious and was also confirmed by the range of their confidence limits (Fig 2). A large difference resulted from total bonding according to the confidence limits of groups E and F. Parametric standard data of all groups are listed in Table 1.

Catastrophic failure occurred with two fracture patterns. All crowns in the groups A to E were represented by an exclusive adhesive fracture pattern as shown by Fig 3: complete cracks through the ceramic resulting mostly in a separation of one single labial fragment from the die at the cement-metal interface. A different fracture pattern was only observed in group F: more complex types of crack propagation, complete or incomplete, yielded adhesive and cohesive fractures with the separation of several smaller fragments within the ceramic, at the ceramic-resin interface, and at the resin-metal interface (Fig 4).

Statistical Analysis

The results of the Kolmogorov-Smirnov test yielded no evidence to reject the null hypothesis of a normal distribution of the data sets. $P$ values ranged from .51 to .96. D values were less than or equal to 0.18. Therefore, parametric methods were used for statistical analysis.

Analysis of variance of the groups A, C, and E using Bonferroni adjustment revealed significant differences from E to A and from E to C ($P < .01$), whereas A and C were from the same population. Therefore, evidence can be assessed to the increased values of resin luted crowns (E) compared to crowns luted using zinc phosphate or glass-ionomer cements (A and C).

The groups A and B (without $A_{12}$ and $B_{12}$), C and D, and E and F were compared according to Student's $t$ test for comparison of paired data. The critical $t$ values $t_{\text{XY}}$ were: $t_{\text{AB}} = \pm 2.878$ (18 degrees of freedom, two tailed mode, $P < .01$); $t_{\text{CD}} = t_{\text{EF}} = \pm 2.861$ (19 degrees of freedom, two tailed mode, $P < .01$). The calculated $t$ values $t_{\text{XY}}$ were: $t_{\text{AB}} = 0.699$ (in between the acceptance range of the null hypothesis), $t_{\text{CD}} = -2.16$ (also in between the acceptance range), and $t_{\text{EF}} = -12.69$ much less...
Cementation Modes and Fracture Resistance of Crowns

Fig 2 Ninety-five percent confidence interval of the data set means of groups A to F (n = 119).

Fig 3 Crown B5 after fracture, representative of the fracture pattern of all crowns in the groups A to E.

Fig 4 Crown F2 after fracture showing the different fracture pattern of the crowns with adhesive bonding to the die in group F.

Discussion

The preparation design of the steel testing dies in the shape of a maxillary central incisor referred to a well-established and documented clinical indication for all-ceramic crowns.\textsuperscript{2,3,6,9,40} The manu-
facturing of dies and crowns by a copying process yielded practically identical dimensions. Each wax crown was controlled on its related die. Corrections of fit were performed if necessary, but they were strictly limited to the crown margin to achieve an optimum fit. Therefore, these small corrections were assumed to have no practical influence on the dimension of the crowns. However, some variances caused by this proceeding may have contributed to the random error. All crowns had a loose fit without die friction to avoid tensile stress resulting from crown positioning and seating discrepancies during cementation that might have arisen from conditioning and coating of the inner surfaces. The standardized cementation measures were used to yield equivalent cement film thicknesses as the "cement thickness at tooth margin" according to Grajower and Lewinstein. Both seating discrepancies and cement film thickness were supposed to be variables of influence according to the results of in vitro studies. A constant cementation load of 28.7 N appeared to be more suitable than the use of finger pressure. This load was preferred to greater weights to avoid the risk of damage to the ceramic crowns by placing the load cart prior to the crowns being completely cemented. Within a loading time of 5 minutes, the zinc phosphate and glass-ionomer cements had lost most of their flow potential so light polymerization of the resin cemented crowns was initiated at this time. The remains of cement and luting agent after fracture testing in the series A to E showed relatively weak adhesion to the dies. The dies were steam cleaned without damage or affection to the metal surfaces. Several nonspecified factors may have contributed to the variations in fracture load/resistance measurements: application of compressive forces, variations in ceramic thickness, material defects or porosities, different size and depth of surface microdefects, variations of the cement film thickness, cement voids, and variations of the incisal loading points and distributions. These factors are difficult to control and were therefore classified as potential sources of random variation. The use of a tin foil under the loading bar was intended to provide a more equally distributed load area and to level potential stress peaks. According to the breaking mechanism and clinical failure modes of all-ceramic crowns, fractures are initiated by microdefects and scratches on the ceramic surfaces. With respect to the compressive forces, one can assume that stress patterns on the crown walls are more clear the more the proportion of compressive forces can be reduced, because as antiparallel vectors (Fig 5) they are able to compensate an unknown amount for the effective bending stress $\sigma$ at the surface defects. These compressive forces depend on the axial proportion $F_s$ of the incisal load $F_i$ and are supposed to decrease with increasing load angle $\alpha$. Such a situation is similar to, for example, the dynamic functional forces on canines and eccentric forces on front teeth, especially during parafunctions, which are referred to as one cause for the failure of all-ceramic restorations. Thus, a load angle of 45 degrees was used. The relatively low coefficients of variance and close confidence limits of the means ($CV$, $CL$ in Table 1) found in this study were assessed. Not only the tin foil, but also the load angle of 45 degrees, the uniformity of the dies and crowns, and the sample size (twice that reported in many other studies), may have contributed to this effect. After searching the data for statistical outliers, two values, $A_1$ and $F_1$, were removed and the data sets were reevaluated. The recalculated data (see Table 1) showed more evidence for a normal distribution according to the Kolmogorov-Smirnov test: $P$ values increased from .51 to .78 (group A) and from .61 to .88 (group F). The reevaluated differences between the groups appeared clearer. Nevertheless, the statistical analysis was based exclusively on the uncorrected original data sets. The statistical evaluation negated the concept of any improvement of the breaking strength of crowns luted using zinc phosphate or glass-ionomer cement by bonding. This finding was more or less expected, because a thin sealing layer of resin bonding agent on the inner
surface without adhesion to the die would neither prevent or compensate for tensile stress, nor would it transfer such stress to the supporting die structure. In contrast to such a thin sealing film of resin bonding agent, the larger cement film thickness and elastic modulus of a filled resin luting agent as applied in group E seemed to markedly increase the stress resistance of the crowns according to the ANOVA. This was also confirmed by the nonoverlapping confidence intervals of groups A, B, C, D, and E (see Fig 2). The greatest effect was achieved using adhesive cementation to the die in group F. The strengthening effect in vitro was considerable, with an exact significance level of 10-10. The mean fracture load had almost doubled.

Such results often lead to the temptation of making clinical inferences. It must be emphasized that this type of crown testing is generally affected by many unknown variables and shortcomings. Its relation to clinical failure modes is uncertain or even unknown. One strong argument against the clinical inferences of so-called “crunch-the-crown tests” was recently provided by the investigations of Kelly et al. They found that in vitro ball loading of fixed partial dentures and crowns yielded blunt indentation damage, which was far from clinically observed crack and failure origins. Two further problems arise: to date no bonding system for the dentin-resin interface has been proven to provide effective bonding forces equal to the amount shown for the metal-resin interface. The second problem refers to the elastic modulus of the supporting die material. Steel is very rigid whereas dentin has a lower elastic modulus. Bending forces lead to deformation and therefore cause more shear stress at the tooth-cement restoration interface than on a metal die. Furthermore in this study, it was not possible to include two clinically important aspects of failure: static chemical and cyclic mechanical fatigue phenomena of the ceramic and the bonding interfaces and the degradation of luting agents under the conditions of the oral cavity.

Effects similar to the results of this study were reported by other researchers. Grossman and Nelson showed a 66% increase in “load resistance” of in vitro Dicor-restored extracted molars using a resin luting agent as well as dentin and crown conditioning for cementation. Another in vitro study showed a strong enhancement of the “breaking strength” of Dicor crowns bonded to metal dies against nonbonded crowns. These effects were confirmed on dentin and enamel surfaces, giving substantial evidence for the importance of an effective bonding to a strong die material in natural enamel in vitro and in a clinical investigation over 2 years. The significant but smaller effects of resin cementation without effective adhesion to the die material was newly shown in vitro. However, speculations and hypotheses about the beneficial effects of resin agents in “sealing” or “healing” the surface defects of glass ceramics have not been sufficiently confirmed by crown studies. In vitro studies that demonstrate significant strengthening effects by simply modifying certain surface characteristics of ceramic specimens such as surface roughness, crystal lattice structures, microporosity, etc, require further investigation. The key seems to be rather a strong bond and effective stress transfer as achieved in true compound systems represented by the positive control group F of this study. The success of ceramic-related compound systems has widely been proven by the metal ceramic technique and the introduction of the In-Ceram glass infiltration system. Considering the fracture pattern of clinically failed crowns, further studies with a longitudinal design and clinical testing are necessary to evaluate the practical relevance of the results of this study.

Conclusions

Feldspathic pressed ceramic crowns were luted to prepared metal dies using three types of luting agents and varied luting procedures. Within the limitations of this in vitro study design, the following conclusions may be made:

1. The use of zinc phosphate or glass-ionomer cement had no significant influence on the fracture resistance of feldspathic ceramic crowns (mean values: 294 N, 217 N, respectively). However, the use of a resin luting agent yielded a significant increase in fracture resistance (382 N).

2. Additional sealing of the inner surface of the conventionally cemented crowns using a resin bonding agent had no detectable effect on fracture resistance. Fracture resistance was 282 N and 255 N against conventionally cemented crowns without resin sealing as negative controls (294 N and 217 N) and completely adhesive luted crowns as a positive control (688 N).

3. In contrast, complete adhesive bonding using a resin luting agent yielded a considerable increase of the in vitro fracture resistance of feldspathic ceramic crowns. The condition of this effect was a strong bond at both interfaces, the crown-resin and the die-resin interface, simulated by a metal surface conditioner.
Acknowledgments

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CO₂ lasers and temperature changes of titanium implants

This study investigated the temperature changes around titanium implants when a CO₂ laser was used at stage II implant surgery and when it is used to debride exposed threads. To ascertain temperature changes effected during stage II surgery, 28 implants (3.75 × 7, 13, and 20 mm) were placed into fresh, resected pig mandibles using off-the-crest incisions and covered with a gingival flap. Temperature was measured by means of two T-type thermocouples placed on each implant. One thermocouple was placed coronally at a mean of 3.4 mm from the crest of bone, the other was placed apically at a mean of 6.5, 7.6, and 7.3 mm for the 7-, 13-, and 20-mm implants, respectively. Using a “Lase and wipe” technique, a CO₂ laser, with a 0.8-mm orifice ceramic tip, was utilized at 4 to 6 W to uncover the implants. Temperature increases at the coronal thermocouple ranged from 4.2°C to 16.8°C. An increase of 2.0°C to 11.5°C was measured at the apical thermocouple. To assess the effect of lasers on exposed threads, three implants were placed in one arch, as described above, and a 5 × 4 mm bony dehiscence was created. The laser was then used to “decontaminate” the exposed threads. The temperature increased 1.2°C to 11.7°C at the coronal thermocouple and 0.0°C to 5.0°C at the apical thermocouple. Scanning electron micrographs of the sampled implants revealed no gross surface changes of the implants. They also showed the laser’s inability to completely remove saliva and blood from exposed threads.

Oyster DK, Parker WB, Gher ME. J Periodontol 1995;66:1017–1024. References: 45. Reprints: Librarian, Naval Dental School, National Naval Center, 8901 Wisconsin Avenue, Bethesda, Maryland 20889-5602. —Maurine Saucio, DDS, Department of Prosthodontics, New York Department of Veterans Affairs Medical Center, New York, New York