APPENDIX E

APPENDIX E

Bibliography and Copies of Published Literature

Bibliography

The following articles were returned in response to a search of the English language literature using the PubMed search engine and the keywords "CEREC AND adverse events," "CEREC AND complications," "CEREC AND risks" and "CEREC AND injuries."

1. Bremer BD and Guertsen W: Molar fracture resistance after adhesive restoration with ceramic inlays or resin-based composites. *Am J Dent* 2001, Aug 14(4):216-20.

2. Heymann H, Bayne S, Sturdevant J, Wilder A, Roberson T: The clinical performance of CAD-CAM-generated ceramic inlays: A four-year study. *J Am Dent Assoc* 1996, Aug, 127(8):1171-1181.

3. Krejci I, Lutz F, Reimer M: Marginal adaptation and fit of adhesive ceramic inlays. *J Dent* 1993, Feb, 21(1):39-46.

4. Sjögren G, Molin M, Dijken J, Bergman M: Ceramic inlays (Cerec) cemented with either a dual-cured or a chemically cured composite resin luting agent: A 2-year clinical study. *Acta Odontol Scand* 1995, Oct, 53(5):325-30.

Molar fracture resistance after adhesive restoration with ceramic inlays or resin-based composites

Bernd D. Bremer, DDS, Dr Med Dent & **Werner Geurtsen**, DDS, Dr Med Dent, PhD

Abstract: ***Purpose:*** To determine the fracture resistance of teeth, following treatment with various types of adhesive restorations. ***Materials and Methods:*** 50 caries-free, extracted human molars were randomly divided into five groups consisting of 10 molars each. MOD cavities were prepared in 40 molars with a width in the facio-lingual direction of 50% of the intercuspal distances. The cavities were filled with the following materials: Cerec or IPS Empress ceramic inlays, Arabesk or Charisma F resin-based composite (RBC) restorations. The control group consisted of 10 sound, non-restored molars. All 50 teeth were loaded occlusally until fracture using a tensile testing machine. The statistical analysis included ANOVA, Kolmogorov-Smirnov-test, Scheffé-test, and boxplots. ***Results:*** There was no significant difference ($P > 0.05$) between the mean values of the sound teeth (2,102 N) and the teeth with the Cerec ceramic inlays (2,139 N). However, both groups demonstrated a significant difference ($P < 0.05$) when compared with the teeth with IPS Empress ceramic inlays (1,459 N) and Arabesk RBC restorations (1459 N). No significant differences were found between the last two groups. Molars restored with Charisma F composite restorations (1,562 N) revealed no significant difference when compared with all other groups including controls ($P > 0.05$). A stabilization of molars is possible by means of an adhesive restoration in the form of an "internal splinting" regardless of the restorative material used. (*Am J Dent* 2001;14:216-220).

Clinical significance: Fracture resistance of molar teeth with a cavity width of 50% of the intercuspal distance can be fully restored by bonded inlays made with a prefabricated ceramic (Cerec). The fracture strength observed with those restorations reached values similar to sound non-restored molars.

Correspondence: Prof. Dr. W. Geurtsen, Department of Conservative Dentistry & Periodontology, Medical University Hannover, D-30623 Hannover, Germany, Fax:++49-511-5324811, E-mail: geurtsen.werner@mh-hannover.de

Introduction

Since the first comprehensive report on the "cracked tooth syndrome" by Cameron[1] in 1964, several investigations have shown that fractures of teeth, particularly after being filled, frequently resulted in tooth loss.[2-4] Fisher *et al*[5] demonstrated that stabilization of the tooth after an intracoronal preparation can be achieved by covering the outer surface with a cast metal onlay. This procedure involves, however, an additional loss of healthy dental hard tissues and in case of full coverage restorations, may lead to a marked reduction in esthetic appearance. As an alternative to this "external splinting", a number of studies[6,12,14,24,25] investigated the suitability of the adhesive technique in order to get an "internal splinting" for the stabilization of weakened teeth. For these adhesive restorations, no additional dental hard tissue is removed, preserving tooth structure and, at the same time, providing an esthetic and functional restoration.

Depending on the extension of the cavity, the restorative treatment is a predisposing factor for an incomplete or complete tooth fracture.[7,8] Jokstad *et al*[9] reported tooth fracture in more than 15% of cases (for teeth with amalgam restorations), in a study of 10,091 treatments with different restorative materials. In order to protect a weakened tooth, coverage of the outer tooth surface is recommended (onlay, overlay, inlay with cuspal coverage, partial and full crowns).[5,6,10,11] For esthetic purposes, tooth colored materials using adhesive techniques were investigated for stabilization of teeth. Haller *et al*[12] reported a higher degree of cuspal reinforcement with onlays and adhesive inlays made of resin-based composite (RBC) and ceramic. Lang *et al*[13] demonstrated a lower degree of cuspal flexure with ceramic and RBC inlays than with metal inlays. In both studies,[12,13] RBC and ceramic inlays were adhesively bonded to enamel only.

Due to the very limited data available on fracture resistance of adhesively restored teeth based on clinically realistic cavity dimensions it was decided to 1) determine fracture strength of human molars restored with ceramic inlays or RBC restorations, and 2) to evaluate whether various products (two ceramic and two RBCs) may significantly influence the degree of stabilization.

Materials and Methods

Fifty extracted, caries-free human molars were used. The radicular surface of all teeth was cleaned by removing residual desmodontal fibers and calculus. Thereafter, each tooth was carefully examined visually under x2 magnification for any existing enamel fissures or infractions. Only flawless teeth were included in this study. Finally, all teeth were perpendicularly embedded in stone plaster (Tewestone[a]) up to 1 mm below the enamel-cementum-junction. From the 50 embedded teeth, 10 were randomly selected, not subjected to any further treatment and served as controls.

The remaining 40 teeth were subjected to preparation of MOD cavities made with diamond burs[b] under a constant flow of cool water. The width of the cavities in the facio-lingual direction was approximately 50% of the intercuspal distance (Fig. 1). The extension of the proximal boxes and the cavity

Table 1. Mean values and standard deviations of the cavity dimensions in each group (CE = Cerec inlays, EM = IPS Empress inlays, AR =Arabesk-restorations, CH = Charisma F-restorations); for definition of the cavity dimensions and abbreviations see Figs. 1 and 2

Group	Mean value B:A (%)	Standard deviation (%)	Mean value F:E (%)	Standard deviation(%)	Mean value H:G (%)	Standard deviation (%)
CE	50.13	0.67	50	0.27	50.16	0.23
EM	50.02	0.9	50.03	0.55	50.01	C.50
AR	49.78	0.67	49.91	0.43	49.78	C.38
CH	50.06	0.44	49.9	0.47	49.68	C.6

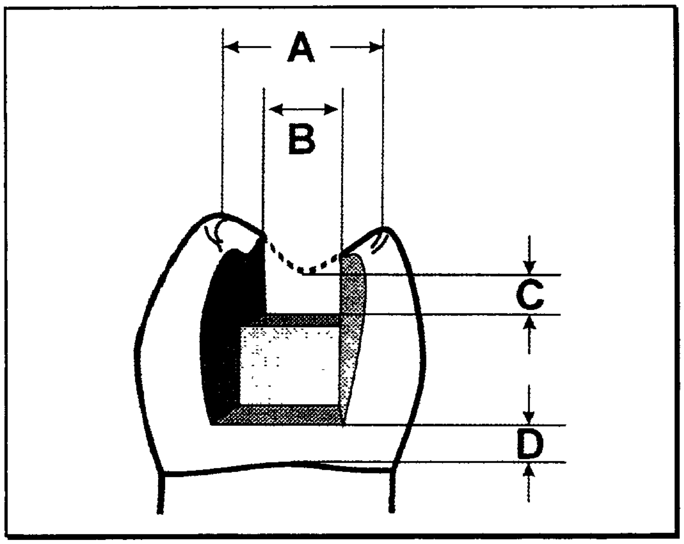

Fig. 1. Cavity dimensions, proximal view: The occlusal cavity width (B) was approx. 50% of the intercuspal distance in an oro-vestibular direction (A), the cavity depth in the occlusal area was appr. 2mm (C), and the distance between the cervical margin of the proximal boxes and the enamel-cementum-junction was appr. 2mm as well (D).

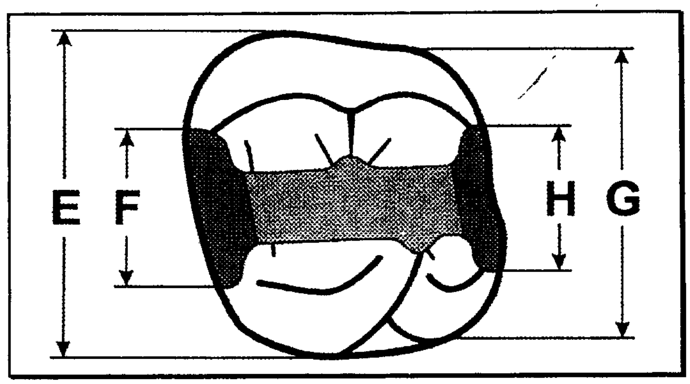

Fig. 2. Cavity dimensions, occlusal view: The horizontal width of the proximal boxes (F resp. H) was 50% of the reference values E resp. G.

depth in the occlusal area are shown in Fig. 2. These dimensions were determined individually for each molar tooth. For this, the teeth were measured using a digital gauge. During preparation the proximal and occlusal cavity dimensions were repeatedly checked with a digital gauge as well. All cavity walls demonstrated a slight conicity only, the occusal cavity floor and the base of the proximal boxes were horizontally prepared and leveled. The inner cavity angles were rounded. After preparation, the proximal enamel margins were contoured with a gingival margin trimmer. The pulpal aspects of the cavities were lined with a thin layer of glass-ionomer cement (Ketac-Bond Aplicap[c]).

The 40 prepared teeth were randomly divided into four experimental groups of 10. The cavities were restored with two different types of ceramic inlays and two RBCs. All restorations were adhesively bonded to enamel and non-lined dentin: Cerec[d] ceramic, IPS Empress[e] ceramic, Arabesk[f] RBC, and Charisma F[g] RBC. The materials were applied according to the manufacturers' instructions. Enamel margins were acid-etched with 37% phosphoric acid gel (Ätzgel Minitip[c]) for 60 s, then thoroughly rinsed with water (20 s) and air-dried for another 20 s. Both ceramics were etched with 5% hydrofluoric acid (Vita Ceramics Etch[h]) for 60 s, thoroughly rinsed with water for 60 s, and air-dried for 20 s. Cerec inlays were silanized with Silicoup[g] whereas Empress ceramic was silanized with Monobond S.[e] Prior to insertion, the silanized surface of the ceramic inlays and the cavities were covered with a bonding agent (Heliobond[e]). A dual curing RBC (Dual Cement Radiopaque[e]) was used for adhesive cementation of the ceramic inlays. The RBC cement was light-cured occlusally and from all proximal aspects for 60 s each (Elipar[c]).

After all cavity walls were covered with the bonding agent, RBC was placed in the cavities in increments of 1 mm thickness. Each individual layer was light-cured for 60 s (Elipar) The intensity of the curing light was regularly monitored with a light meter. The final layer of RBC material served to form the occlusal relief and proximal surface, and was then light-cured again.

Following restoration and finishing, all specimens of the experimental groups and the controls were stored for 1 wk in sterile, physiological saline solution at room temperature. Further procedures were identical for all groups. A steel ball[i] with a diameter of 2mm was placed in the central fissure of each tooth. By means of a tensile testing machine,[j,k] a loading force was applied over the steel ball occlusally to the teeth in a vertical direction until fracture. The loading force of the tensile testing machine was 5mm/min (crosshead speed). A strip chart recorder registered the conducted force. At a 100 N decrease of power it was assumed that the "fracture" had taken place and the procedure was automatically discontinued. A diagramatic view showing the experimental design can be seen in Fig. 3. After fracture, all teeth were photographed and the modes of fracture were analysed.

Data were statistically evaluated with SPSS. Means, standard deviations, minimum and maximum were calculated. Statistically significant differences were evaluated by the

Table 2: Minimum, maximum, mean and standard deviation of the fracture values (N) (C = controls, CE = Cerec inlays, EM = IPS Empress inlays, AR = Arabesk-restorations, CH = Charisma F-restorations) (n = 10 for each group). Statistically significant differences (P< 0.05) of the fracture values between various groups are marked with an asteriks (*).

Group	Minimum (N)	Maximum (N)	Mean value (N)	Standard deviation (N)
C	1320	3160	2102	521
CE	1650	2920	2139	404
EM	853	2510	1459 *C,Ce	501
AR	934	2099	1459 *C,Ce	348
CH	844	2193	1562	403

Table 3: Fracture analysis of control teeth and experimental groups; four different types of tooth fracture were observed: complete loss of one isolated cusp ("cuspal fracture"), complete fracture of the oral or vestibular wall ("wall fracture"), vertical fracture of the tooth in the mesio-distal or vestibular-oral direction ("vertical fracture"), or splintering of the crown into several pieces ("crown fracture").

Group (n = 10)	Cuspal fracture (n)	Wall fracture (n)	Vertical fracture (n)	Crown fracture (n)	Restoration fracture (n)
C	4	4	2	-	/
CE	3	4	3	-	10
EM	6	2	2	-	10
AR	6	1	3	-	10
CH	3	1	5	1	10

Kolmogorov-Smirnov test (P< 0.05), one-way ANOVA using the Scheffé test, and boxplots.

Results

The "relative" cavity dimensions of each individual tooth, *i.e.*, cavity extensions related to tooth size, were checked with a digital gauge during preparation to ensure similar conditions. The values were noted for each tooth (Table 1, Figs. 1, 2). The comparison of the mean cavity dimensions of the various experimental groups revealed no significant differences (P 0.05).

The fracture values (in N) of all experimental groups and the controls were determined. The minimum, maximum, mean values, and the standard deviations of the groups are in Table 2. The recorded values from each group were checked for the test distribution. Control of these values was carried out with the Kolmogorov-Smirnov test and revealed normal test distribution for all groups. Consequently, a mean value comparison of the individual groups could be achieved by a unifactorial analysis of variance (ANOVA and Scheffé test). The significance level was assessed at 95% (Table 2).

Significant differences were noted between the control group and the experimental groups restored with IPS Empress ceramic inlays and Arabesk RBC restorations. This indicated that the fracture resistance of the non-treated teeth was significantly higher (P< 0.05) than those of the groups with IPS Empress inlays and Arabesk restorations. The fracture values of the group with Cerec inlays were also significantly higher than those of the groups with IPS Empress inlays and Arabesk restorations. No significant difference, however, was demon-

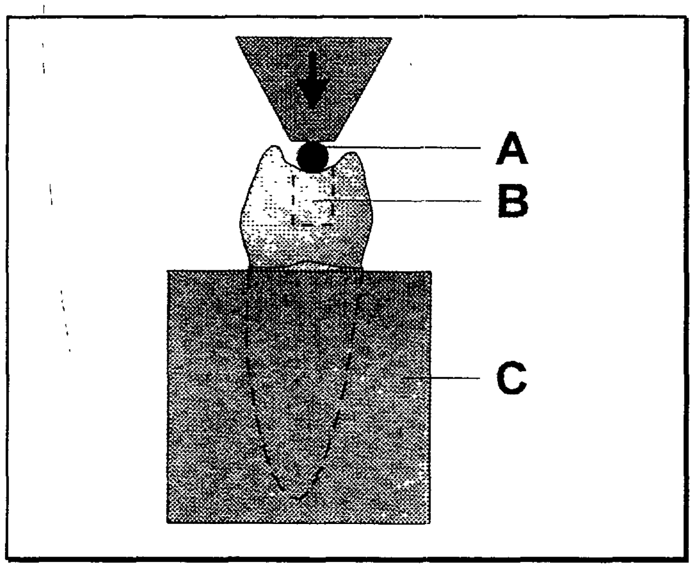

Fig. 3. Diagramatic view of the fracture experiment: All filled teeth and sound controls were centrally loaded until fracture in a testing machine with a force of 5mm/min (A = steel ball, diameter: 2mm; B = restoration; C = molars were embedded perpendicularly in stone plaster).

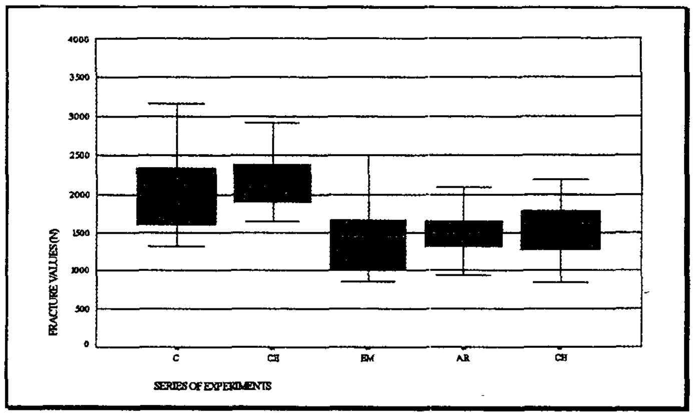

Fig. 4. Boxplots of the fracture resistances (N) in dependence upon the restoration.

strated between the control group and the Cerec inlays, also between these groups and Charisma F restorations. Likewise, there was no significant difference between the IPS Empress inlays and the Arabesk restorations, and between these groups and the Charisma F restorations. Fig. 4 shows a boxplot diagram (maximum, minimum, median, 75% and 25% percentile) of the results of this study.

The analysis of the fracture modes is summarized in Table 3. Four different types of fractures were observed: complete loss of one isolated cusp ("cuspal fracture"), complete fracture of the oral or vestibular wall ("wall fracture"), vertical fracture of the tooth in the mesio-distal or vestibular-oral direction ("vertical fracture"), or splintering of the crown into several pieces ("crown fracture"). The fracture behavior of the teeth restored with Cerec-Inlays was very similar to the control group. Predominantly, cohesive cuspal and wall fractures within the tooth structure were observed in the Cerec group. Specimens with Empress ceramic inlays and Arabesk RBC restorations, however, showed mainly cuspal fractures with loss of an individual cusp. To the contrary, specimens of the Charisma group often revealed vertical fractures. No adhesive failures were observed (Table 3).

Discussion

The fracture resistance of a filled tooth can be significantly affected by several factors, in particular cavity dimension and type of restoration material.[14] Various authors have investigated the correlation between expanse and design of a cavity on the one hand and the fracture resistance of teeth. Re *et al*[15-18] concluded from their data that neither extension nor form of a cavity significantly influence the fracture resistance of teeth. Eames & Lambert,[19] however, contradicted these results and stated that those studies had been carried out using "unrealistic" standard cavities. Subsequently, Re *et al*[20] observed that a decrease of fracture resistance is caused by an increase of cavity expanse and depth as well. These results were confirmed by various authors based on experimental and clinical observations.[7,14,21-30] In addition, comprehensive epidemiological studies revealed an increased frequency of tooth cracks in association with extensive restorations.[11,31] Interestingly, it was determined in a clinical survey with 610 restorations that the average cavity width of amalgam restorations was 50% of the oro-vestibular intercuspal distance.[32]

The contradictory results of various authors underline the difficulties with the design of studies about fracture resistance of posterior teeth.[33] On account of size variation, *e.g.*, standard cavities with uniform dimensions in all specimens will weaken extracted human molars or premolars differently. Due to these problems, cavities with a width of approximately 50% of the facio-lingual intercuspal distance were prepared for our experiments. Further, it must be emphasized that this cavity expanse was individually calculated for each molar used in our study. Thus, similar prerequisites were ensured for each restored tooth regarding cavity width in contrast to other investigations. In those studies, except for Reel *et al*,[34] only standard cavities were applied varying between 1.5 and 2mm in the facio-lingual direction regardless of the individual dimensions of the investigated teeth (for review see Geurtsen & García-Godoy[33]). This approach inevitably resulted in significantly different fracture resistance of the various teeth after cavity preparation which, therefore, limits comparability of the results found by those researchers.

Another study[35] reported that dentin adhesives can weaken the interface between dentin and RBC materials. Further, it was observed that a bonded interface in dentin tends to produce microscopic flaws which may have an effect as critical stress risers resulting in interfacial failures.[36] In addition, it was reported previously, that RBC and ceramic inlays solely bonded to enamel can stabilize weakened teeth.[12,13] Thus, ceramic as well as RBC restorations were adhesively bonded to enamel only in order to prevent detrimental stress peaks with subsequent flaws at the dentin interface. This approach was corroborated by our fracture analysis indicating predominantly cohesive fractures of the tooth structure whereas no adhesive failures at the interface between the restorations and dentin or enamel were observed. Therefore, it may be concluded from our data and the results reported from other authors as well that the total bonding technique will not increase fracture resistance in comparison to sole enamel bonding.[35,36]

The findings of the present study with comparable relative cavity dimensions show that stabilization of a weakened tooth can be achieved with a restoration adhesively bonded to enamel. However, not all materials included in our experiments resulted in fracture strengths which are similar to healthy teeth. Fracture resistance of molars restored with Cerec ceramic inlays was comparable to values found with sound non-restored teeth. But IPS Empress ceramic inlays on the other hand, resulted in a significantly lower fracture strength in comparison to non-restored controls. Interestingly, IPS Empress is characterized by a lower flexural strength (120 MPa) than Cerec ceramic (130 MPa) according to the manufacturers' information. It may be speculated, therefore, that the higher flexural strength of Cerec ceramic may slightly contribute to the higher fracture resistance of molars filled with Cerec inlays in comparison to Empress inlays.

Little data about ceramic inlays (Cerec ceramic) and ceramic inserts are available in the dental literature. "Semidirect" ceramic restorations significantly stabilized weakened teeth after cavity preparation. Further, it has been also stated that prefabricated ceramic inserts may improve the distribution of occlusal masticatory forces and consequently may reduce strain peaks.[36,37] Thus, our results and the literature data as well reveal that the type of ceramic is of decisive importance regarding fracture stability. Physical parameters, in particular flexural strength, however, seem to be of minor importance. These data indicate that ceramic systems prefabricated under optimal conditions (Cerec ceramic, prefabricated ceramic inserts) generally may re-establish fracture stability whereas ceramic processed in the dental laboratory (IPS Empress ceramic) do not completely restore fracture resistance of the teeth.

Interestingly, similar findings were made with the investigated two modern hybrid type RBCs. Molars restored with one product (Charisma F; compressive strength: 380 MPa) revealed fracture values which were lower but not significantly different from the sound controls. It must be considered, however, that stabilization due to this product was also not significantly different from values observed with the "weaker" laboratory processed ceramic system and the other investigated RBC. But the second investigated RBC product (Arabesk; compressive strength: 360 MPa) resulted in fracture strengths which were significantly lower in comparison to the prefabricated ceramic material and the sound controls as well. Our findings show that modern hybrid type RBCs can significantly increase the stability of filled teeth. The marginal difference of the flexural strength of both investigated RBCs indicates that this parameter should not significantly influence the degree of stabilization.

Very contradictory findings have been published about the effects of adhesive RBC restorations on fracture strength.[34] Some researchers reported that RBC, especially in addition to a dentin adhesive, can increase the stability of filled teeth to values found with non-restored healthy controls.[28] But other scientists described a significantly lower fracture resistance of teeth adhesively restored with RBC with or without dentin bonding agent.[14,33,39,40] This great variation may be at least partially explained by the different ("standard") cavity dimensions and the various restoration materials which have been applied by different researchers.

a. Kettenbach Co., Tuttingen, Germany.
b. Komet, Lemgo, Germany.
c. ESPE, Seefeld, Germany.
d. Sirona, Bensheim, Germany.
e. Ivoclar-Vivadent, Schaan, Liechtenstein.
f. Voco, Cuxhaven, Germany.
g. Hereaus-Kulzer, Wehrheim, Germany.
h. Vita, Bad Säckingen, Germany.
i. SKF Co., Germany.
j. Zwick & Co., Ulm, Germany.
k. UTS Testsysteme, Ulm, Germany.

Dr. Bremer is Senior Lecturer at the Department of Prosthodontics, and Dr. Geurtsen is Professor and Chairman at the Department of Conservative Dentistry & Periodontology, Medical University Hannover, Hannover, Germany.

References

1. Cameron CE. Cracked-tooth syndrome. *J Am Dent Assoc* 1964; 68: 405-411.
2. Braly BV, Maxwell EH. Potential for tooth fracture in restorative dentistry. *J Prosthet Dent* 1981; 45: 411-414.
3. Wright EF. Diagnosis, treatment, and prevention of incomplete tooth fractures. *Gen Dent* 1992; 40: 390-399.
4. Shillingburg HT, Jacobi R, Brackett SE. *Fundamentals of tooth preparations for cast metal and porcelain restorations.* Chicago: Quintessence Pub. Co, 1987, 237-258.
5. Fisher DW, Caputo AA, Shillingburg HT, *et al.* Photoelastic analysis of inlay and onlay preparations. *J Prosthet Dent* 1975; 333: 47-53.
6. Geurtsen W, Hullmann U, Gockel HW. Indirect manufactured inlay/ onlay restorations made by composite (II). *Quintessenz* 1988; 10: 1675-1683.
7. Mondelli J, Steagall L, Ishikiriama, A, *et al.* Fracture strength of human teeth with cavity preparations. *J Prosthet Dent* 1980; 43: 419-422.
8. Sheth JJ, Fuller JL, Jensen ME. Cuspal deformation and fracture resistance of teeth with dentin adhesives and composites. *J Prosthet Dent* 1988; 60: 560-569.
9. Jokstad A, Mjör IA, Qvist V. The age of restorations in situ. *Acta Odontol Scand* 1994; 52: 234-242.
10. Geurtsen W. Metallic restorations as an alternative to amalgam. *Dtsch Zahnärztl Z* 1994; 49: 853-858.
11. Pieper K, Betas J, Motsch A. Prevalence of cracked tooth syndrome - A transillumination study. *Dtsch Zahnärztl Z* 1994; 49: 822-824.
12. Haller B, Thull R, Klaiber B, *et al.* Ridge stabilization with adhesive inlays in MOD cavities. *Dtsch Zahnärztl Z* 1990; 45: 660-663.
13. Lang H, Schwan R, Nolden R. Deformation of filled teeth. *Dtsch Zahnärztl Z* 1994; 49: 812-815.
14. Geurtsen W, Orth M, Gartner A. The fracture resistance of human maxillary molars with MOD amalgam or composite fillings. *Dtsch Zahnärztl Z* 1989; 44: 108-110.
15. Re GJ, Draheim RN, Norling BK. Fracture resistance of mandibular molars with occlusal class I amalgam preparations. *J Am Dent Assoc* 1981; 103: 580-583.
16. Re GJ, Norling BK, Draheim RN. Fracture strength of molars containing three surface amalgam restorations. *J Prosthet Dent* 1982; 47: 185-187.
17. Re GJ, Norling BK. Forces required to crack unfilled and filled molar teeth. *J Dent Res* 1980; 59: 351.
18. Re GJ, Norling BK. Fracturing molars with axial forces. *J Dent Res* 1981; 60: 805-808.
19. Eames WB, Lambert RL. Fracture resistance of molars. *J Am Dent Ass* 1982; 104: 13.
20. Re GJ, Norling BK, Draheim RN. Fracture resistance of lower molars with varying faciocclusolingual amalgam restorations. *J Prosthet Dent* 1982; 47: 518-521.
21. Grimaldi JR, Hood JAA. Lateral deformation of the tooth crown under axial cuspal loading. *J Dent Res* 1973;52:584.
22. Cameron CE. The cracked tooth syndrome: Additional findings. *J Am Dent Ass* 1976; 93: 971-975.
23. Goel VK, Khera SC, Senthil G, *et al.* Effect of cavity design on stresses in first molars. *J Dent Res* 1985;64:350.
24. Joynt RB, Wieczkowski G, Klockowski R, *et al.* Fracture resistance of teeth restored with amalgam *versus* composite resin. *J Dent Res* 1985; 64: 350.
25. Joynt RB, Wieczkowski G, Klockowski R, *et al.* Effects of composite restorations on resistance to cuspal fracture in posterior teeth. *J Prosthet Dent* 1987;57:431-435.
26. Eakle WS, Maxwell EH, Braly BV. Fractures of posterior teeth in adults. *J Am Dent Assoc* 1986; 112: 215-218.
27. Gher ME, Dunlap RM, Anderson MH, *et al* Clinical survey of fractured teeth. *J Am Dent Assoc* 1987; 114: 174-177.
28. Oliveira FC, Denehy GE, Boyer DB. Fracture resistance of endodontically prepared teeth using various restorative materials. *J Am Dent Assoc* 1987; 115: 57-60.
29. Howe CA, McKendry DJ. Effect of endodontic access preperation on resistance to crown-root fracture. *J Am Dent Assoc* 1990; 121: 712-715
30. Goel VK, Khera SC, Gurusami S, *et al.* Effect of cavity depth on stresses in a restored tooth. *J Prosthet Dent* 1992; 67: 174-183.
31. Veltmaat A, Günay H, Geurtsen W. *In vivo* study of epidemiology of the cracked-tooth syndrome of restored posterior teeth. *Dtsch Zahnärztl Z* 1997; 52: 137-140.
32. Jokstad A. The dimensions of everyday class-II cavity preparations for amalgam. *Acta Odontol Scand* 1989; 47:89-99.
33. Geurtsen W, García-Godoy F. Prevention and treatment of the cracked-tooth syndrome by bonded restorations. *Am J Dent* 1999, 12: 266-270
34. Reel DC, Mitchell RJ. Fracture resistance of teeth restored with class II composite restorations. *J Prosthet Dent* 1989; 61: 177-180.
35. Khajotia SS, Dhuru VB, Fournelle RA, *et al.* Fracture toughness and load relaxation of dentin bonding resin systems. *Dent Mater* 1997; 13: 151-156
36. Toparli M, Aksoy T. Fracture toughness determination of composite resin and dentin/composite resin adhesive interfaces by laboratory testing and finite element models. *Dent Mater* 1998; 14: 287-293.
37. Kunzelmann KH, Obermeier TH, Mehl A, *et al.* Finite element analysis of megafillers/Inserts to optimize shape and material properties. *J Dent Res* 1995; 74: 187.
38. Roznowski M, Bremer BD, Geurtsen W. Fracture resistance of human molars restored with various filling materials. In: Moermann WH (ed.). *Proceedings of the International Syposium on Computer Restorations.* Chicago: Quintessence Pub. Co, 1991; 559-566.
39. Wendt SL, Harris BM, Hunt TE. Resistance to cusp fracture in endodontically teeth. *Dent Mater* 1987;3:232-235.
40. Oliveira F de C, Denehy DE, Boyer DB. Fracture resistance of endodontically prepared teeth using various restorative materials. *J Am Dent Assoc* 1987; 115: 57-60.

HARALD O. HEYMANN, D.D.S., M.ED.; STEPHEN C. BAYNE, M.S., PH.D.; JOHN R. STURDEVANT, D.D.S.; ALDRIDGE D. WILDER JR., D.D.S.; THEODORE M. ROBERSON, D.D.S.

THE CLINICAL PERFORMANCE OF CAD-CAM–GENERATED CERAMIC INLAYS

A FOUR-YEAR STUDY

ABSTRACT The authors conducted a long-term clinical study of 50 CEREC (Siemens AG) CAD-CAM inlay restorations in 28 patients. After four years, they found the inlays to rate very highly in color matching, interfacial staining, secondary caries, anatomic contour, marginal adaptation, surface texture and postoperative sensitivity. They monitored cement loss along the occlusal margins and found it to be relatively low, with an unusual decrease in measured cement wear from the third to the fourth year. The favorable results of this long-term clinical study of these CAD-CAM restorations portend significant success for this restorative approach.

Computer technology has revolutionized restorative dentistry. Already, numerous computer-assisted design/computer-aided manufacturing, or CAD-CAM, systems—such as the Duret system (Duret CAD-CAM, Hennson International)[1,2]; the CEREC system (Siemens AG)[3-8]; and the DentiCAD system (Bego)[9-11]—as well as newer copy milling systems[12] have been developed and marketed for the fabrication of dental restorations. These systems have met with mixed success.

The original Duret system was highly sophisticated, involving complex imaging and computer design. It was used primarily to fabricate full crowns; however, since its introduction, both the original system and the derivative version (the Sopha system, Sopha Bioconcept Inc.) have had limited commercial success. The DentiCAD system was designed primarily for crown fabrication and uses a pen digitizer that allows intraoral digitization of the preparation. It is now marketed for dental laboratory use in Europe by Bego. Other CAD-CAM systems, most of which are laboratory-based, also exist or are being developed primarily for crown fabrication.[13]

Copy milling systems became commercially available at about the same time as CAD-CAM systems. CELAY (produced by Mikrona and marketed in the United States by Vident) can produce inlays by copy milling the same types of materials used in CAD-CAM systems.[14] The ProCera System (Nobelpharma USA) originally was designed to cre-

TABLE 1

MATERIALS AND EQUIPMENT INVOLVED IN PLACEMENT OF CEREC RESTORATIONS.

MATERIALS/ EQUIPMENT	NAME (MANUFACTURER)	DESCRIPTION
CAD-CAM Unit	CEREC [illegible] (Pelton & Crane, Siemens AG)	First-generation COS version [illegible] Software, H-Drive
Reflective Coating Spray	CEREC Powder (L.D. Caulk)	Titanium dioxide and talc
Ceramic Restoration Blanks	Dicor MGC (L.D. Caulk)	65 percent fluorosilicic mica crystals in 35 percent glass matrix
Calcium Hydroxide Liner	VLC Dycal (L.D. Caulk)	Light-cured resin-modified Dycal
Glass Ionomer Liner	Vitrebond (3M Dental Products)	Visible light-cured resin-modified glass ionomer
Dentin Bonding Agent	Gluma (Heraeus Kulzer)	16 percent EDTA conditioner; HEMA; 5 percent glutaraldehyde
Enamel Etchant	Gluma Etching Gel (Heraeus Kulzer)	37 percent phosphoric acid
Enamel Bonding Agent	Heliobond (Ivoclar Vivadent)	Unfilled resin
Ceramic Etchant	Dicor Etching Gel (L.D. Caulk)	Ammonium bifluoride
Ceramic Coupling Agent	Scotchprime (3M Dental Products)	Silane
Composite Luting Cement	Dual Cement (Ivoclar Vivadent)	60 percent fumed silica in urethane [illegible] methacrylate (homogeneous microfill)
Light-Curing Unit	Optilux 400 (Demetron/Kerr)	Visible light-curing unit
Diamond Finishing Instruments	2855F, [illegible] (Brasseler USA)	Ellipse-shaped; flame-shaped
Slow-Speed Polishing Points	Porcelain [illegible] polishing kit (Shofu Dental)	[illegible] polishing points
30-Fluted Carbide Burs	9406, 9803 (Gendex Midwest)	Ellipse-shaped; flame-shaped, bullet end
Polishing Paste	Truluster porcelain polishing paste (Brasseler USA)	Diamond particles of 2-5 μm

ate titanium crowns using copy milling and spark erosion technologies.[12,15-17] It now is intended primarily for milling implant system restorations.

The ceramic reconstruction, or CEREC, system, originally developed by BRAINS AG, was the first fully operational CAD-CAM system marketed for use in clinical dentistry. Although limited to inlays, onlays and veneers, the CEREC system has enabled dentists to design and fabricate a ceramic restoration at the chairside in a single appointment.

In light of the paucity of clinical research on this new technology, we decided to pursue a study to fill this void. We undertook a four-year longitudinal clinical study to evaluate CAD-CAM–generated inlays made from a machinable glass ceramic, Dicor MGC (L.D. Caulk), for a wide range of clinical characteristics, including cement loss at the margins. The study was not designed to test the myriad of

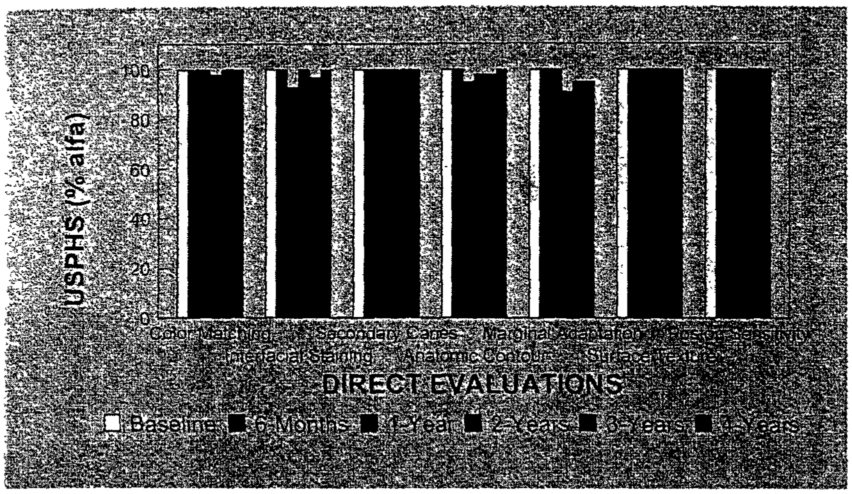

Figure 1. Histogram of percentage of alfa results at baseline, six months, one year, two years, three years and four years for all U.S. Public Health Service categories of evaluation.

potential variables such as cement type or cavity preparation details.

MATERIALS AND METHODS

Table 1 lists the standard materials and equipment we used. Our clinical research methods, as well as the number and the distribution of clinical restorations we studied, were almost identical to those used and examined in previous clinical studies of numerous posterior restorative materials that have been conducted at the University of North Carolina School of Dentistry over the past 20 years.[18-20] These similarities were intentional to allow direct comparison of the long-term performance of CAD-CAM inlays ultimately with dental amalgam restorations and posterior composite resin restorations that acted as control restorations in those previous studies. The most important clinical questions dealt with the wear resistance of the materials and the fracture resistance of the overall design.

Fifty ceramic inlay restorations (Dicor MGC) placed in 28 patients were fabricated using the CEREC system, CEREC Operating System, or COS, version 1.0 software (Siemens AG), a hydro-drive milling unit and standard diamond-tipped milling disks 30 millimeters in diameter. Recent upgrades to the system after our clinical study began included more user-friendly software with icon-referenced options, an electric drive for milling and a larger milling disk (40 mm). This upgraded CEREC system is easier to use and offers improvements in inlay design and fit.

Four clinicians were trained in the use of the CEREC system, and each one performed a minimum of 20 restorations in vitro before the trial began. All cavity preparations and inlay placements were accomplished with rubber dam isolation. Conventional inlay preparations were used that included design modifications to accommodate the unique dynamics of the milling machine.[5,21,22] None of the restorations involved gingival margins that extended into cementum. Most of the restoration sites required amalgam replacement. We deliberately avoided beveling cavosurface margins to facilitate evaluation of wear. We used preoperative wedging with Class II preparations to ensure that adequate proximal contacts were established. A calcium hydroxide liner (VLC Dycal, L.D. Caulk) was used in deep excavations approaching the pulp. We used a light-activated glass ionomer base (Vitrebond, 3M Dental Products) to restore ideal axial and pulpal wall contours where indicated.

The CEREC inlays were fabricated from Dicor MGC, a machinable two-phase ceramic based on fluoroaluminosilicate glass. We etched the internal surfaces of the inlays for 30 seconds with ammonium bifluoride to preferentially dissolve the glassy matrix, rinsed them for 20 seconds and thoroughly dried them with oil-free air. We then coated the etched inlay with a pre-hydrolyzed silane coupling agent (Scotchprime, 3M Dental Products).

All Class II inlays were bonded after placement of a contoured and wedged Mylar matrix band. For bonding, we etched the enamel margins of each tooth with 37 percent phosphoric acid for 30 seconds, rinsed the tooth for 20 seconds and dried it with oil-free air. All dentinal surfaces were conditioned for 30 seconds with ethylenediaminetetraacetic acid (16 percent EDTA), thoroughly rinsed and then primed (Gluma, Heraeus Kulzer). We coated etched enamel and primed dentinal surfaces with a light-activated enamel bonding agent. We followed the bonding agent with an application of a dual-cured microfill composite

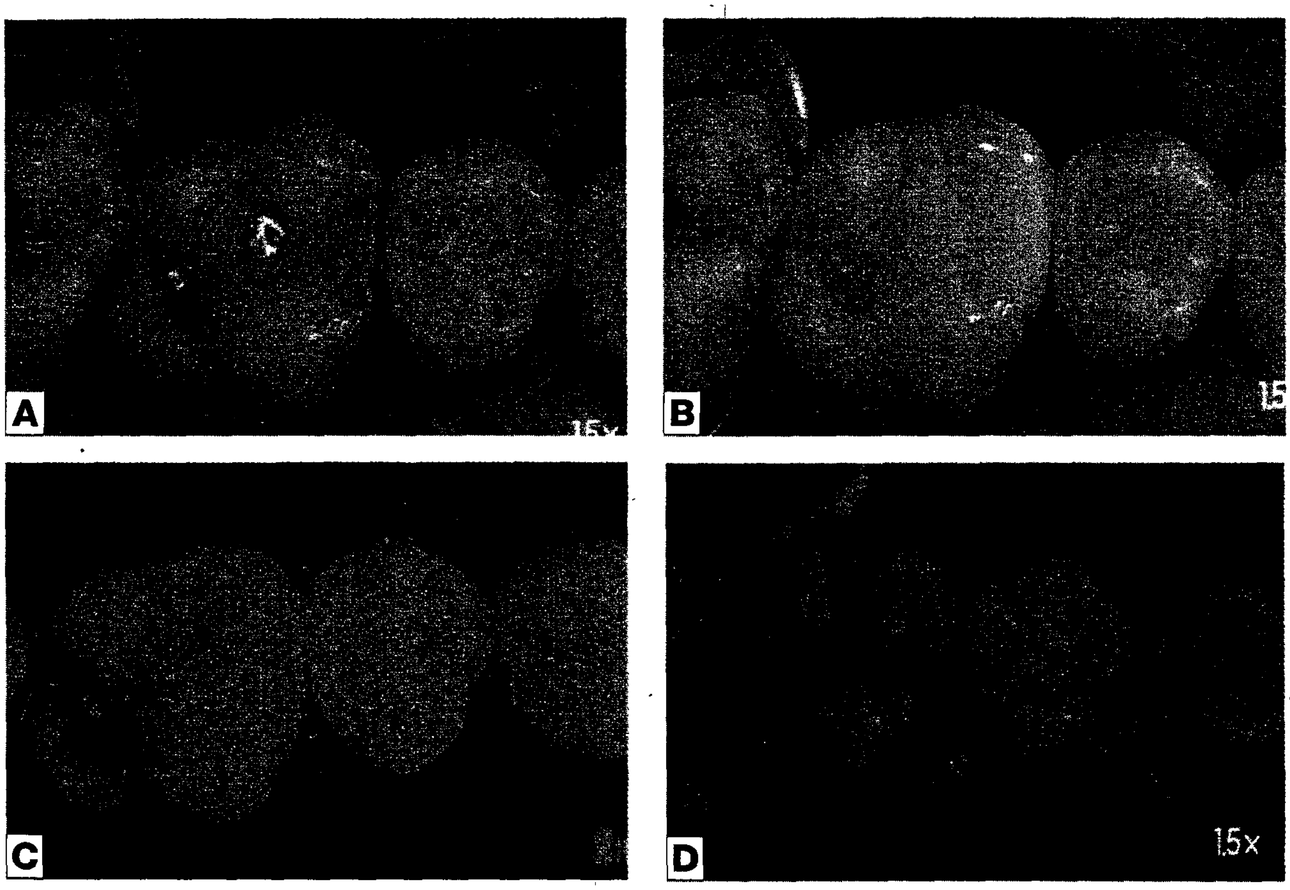

Figure 2. Intraoral photographs of representative CEREC inlay, at 14 months, used to replace an existing amalgam restoration. A. preparation; B. try-in of milled inlay; C. cemented, finished and polished inlay at baseline; D. one-year recall photograph; E. four-year recall photograph.

cement (Dual Cement, Ivoclar Vivadent) to inlay surfaces and then seated the inlay.

We polymerized the cement and bonding agent using a high-intensity visible light-curing unit (Optilux 400, Demetron/Kerr), using 40 seconds of exposure from facial, lingual and occlusal directions. The output of the light-curing unit consistently exceeded 600 milliwatts/centimeter^2 as measured with a curing radiometer (Demetron Research Corp.). After the cement was polymerized, we performed the occlusal contouring and initial finishing of the restorations using a series of fine-diamond instruments with air-water spray and 30-fluted carbide finishing burs.[23,24] We used slow-speed rubber polishing points and diamond polishing paste to carry out the final finishing and polishing (Table 1).

Two clinicians performed direct evaluations at baseline and at each recall using modified U.S. Public Health Service criteria[25] for color-matching ability, interfacial staining, recurrent caries, loss of anatomical form (wear), marginal adaptation and surface texture. In addition, they rated postoperative sensitivity, retention and resistance to fracture. Postoperative sensitivity was defined as absent at recall (alfa), present but not requiring replacement (bravo) or present and requiring replacement (charlie), paralleling the USPHS system of recording clinical changes. The PHS system rated events as un-

TABLE 2

COMPARISON OF GAP WIDTH AND CEMENT LOSS FOR CERAMIC INLAYS OBSERVED IN VITRO AND IN VIVO.*

RESEARCHERS	INLAY SYSTEM	CEMENT TYPE	GAP WIDTH (µm)	CEMENT LOSS (µm)	LENGTH OF STUDY
Heymann (current study)	MGC	DC Cement	—	40	4 years
Moermann and Krejci (1992)[44]	Vita Vita	Duo Cement Heliomolar	149 234	— —	5 years
Moermann and colleagues (1990)[illegible]	Vita	—	—	—	3 years
Isenberg and colleagues (1992)[31]	MGC; Vita	3 cements	80	45	3 years
Gladys and colleagues (1995)[illegible]	MGC Vita MKI	DIC Cement DIC Cement	[illegible] —	— —	[illegible]
Goetsch and colleagues (1990)[53]	—	—	—	—	3 years
Zuellig and Bryant (1995)[illegible]	Vita MKII	4 cements	—	—	2 years
O'Neal and colleagues (1993)[32]	MGC	DC Cement	169	80	2 years
Sjögren and colleagues (1992)[illegible]	Vita MKI or II	[illegible]	[illegible]	—	[illegible]
Essig and colleagues (1991)[43]	MGC MGC MGC	Microfill Hybrid A Hybrid B	— — —	8 51 61	1 year
Thordrup and colleagues (1994)[55]	[illegible]	DC Cement	—	—	1 year
Isenberg and colleagues (1991)[56]	MGC; Vita	3 cements	108	—	0.5 year
Sjögren (1995)[illegible]	[illegible]	[illegible]	[illegible] (occl.) 191 (prox.)	— —	[illegible]
Krejci and colleagues (1993)[58]	MGC Vita MKI	DC Cement Duo Cement	145 (occl.) 133 (prox.) 135 (occl.) 118 (prox.)	— — — —	In vitro In vitro
[illegible]	[illegible]	[illegible]	[illegible] 290 (bevels)	—	[illegible]
Thordrup and colleagues (1994)[60]	Vita	DC Cement	199 (occl.)	—	In vitro
[illegible]	[illegible] Vita (E cut)	[illegible] —	[illegible] 282 (occl.) 258 (prox.)	— — — —	[illegible]
Molin and Karlsson (1993)[62]	Vita	None	123 (occl.) 155 (prox.)	— —	In vitro
Sturdevant and colleagues (1991)[35]	MGC	DC Cement	[illegible] (occl.) 105 (prox.)	[illegible]	[illegible]
Hembree (1995)[63]	MGC	None	90	—	In vitro
Inokoshi and colleagues (1992)[illegible]	Vita	None	52	—	In vitro

*Cement gap widths and cement losses were extracted from larger studies in which many different materials were often compared. Dashes incate that the information was not reported. In some cases, the extracted values were calculated by averaging several reported values within a study. (MGC: Dicor MGC; Vita: Vita MKI or MKII; occl.: value for occlusal cement gap width; prox.: value for proximal cement gap width.)

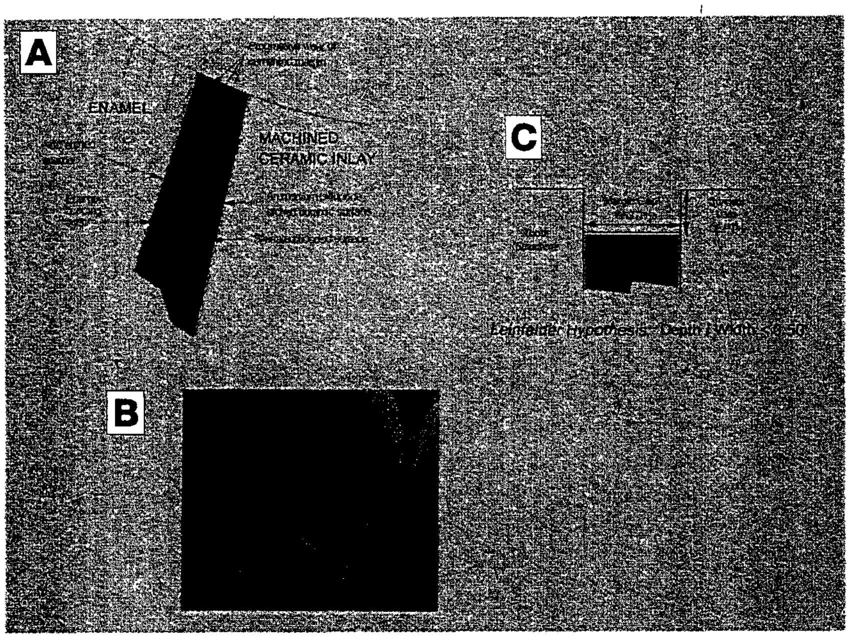

Figure 3. A. Schematic representation of hypothesized wear vs. cement margin width. B. Scanning electron micrograph of cement margin on occlusal surface of mesial-occlusal-distal inlay after four years captured using a stone die from an intraoral impression. The cement margin is visible between the CEREC inlay and enamel. Bubbles along the margin are artifacts. Both the restoration and enamel margin are visible along the entire boundary. C. Schematic representation of the Leinfelder hypothesis for cement wear.[31-33] The ratio of cement loss depth to cement gap width is postulated to be limited to less than 0.50 due to access problems created by the remaining walls of the tooth structure and restoration.

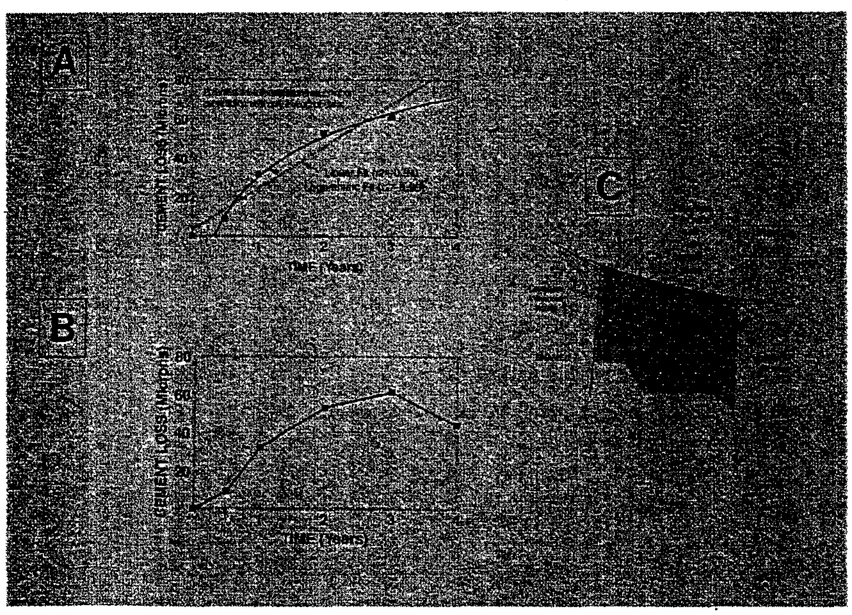

Figure 4. Graph of cement loss (measured by Leinfelder method) as a function of time. A. Regression analysis of baseline to three-year data to demonstrate potential errors of curve fitting and extrapolation. B. Baseline to four-year data showing decrease observed in total wear between third and fourth years. C. Proposed mechanism of inlay margin wear (showing gradual undermining of adjacent enamel and/or inlay margins that then begin to microchip and become rounded off).

detectable change (alfa), detectable but clinically acceptable change (bravo) or clinical failure (charlie). Because we were interested in assessing any clinical change, we reported all data as the percentage of restorations in each category that remained at the alfa level.

Depths of cement wear along the margins were rated on diestone cast replicas of the restored teeth. Casts were compared to a set of standard casts having known amounts of margin wear.[26] Three trained evaluators independently scored all casts at each recall time. They converted the ratings to wear values in micrometers and adjusted them by subtracting the baseline value for wear due to finishing for each restoration. This ensured that errors due to slight overfinishing of the restorations were excluded. The evaluators determined the means of the adjusted values for each recall.

Direct and indirect clinical evaluations were conducted at baseline and at six months, one year, two years, three years and four years after inlay placement. The original distribution of restorations included 38 percent Class I and 62 percent Class II restorations, 42 percent premolar and 58 percent molar teeth, and 34 percent maxillary and 66 percent mandibular teeth.

We monitored cement widths at occlusal margins by viewing stone casts with scanning electron microscopy (Autoscan SEM, ETEC) at ×10 and ×100 magnification. Intraoral color slides of each restoration were collected to document preoperative, preparation, inlay try-in and postoperative conditions. Changes documented from direct evaluations over time were analyzed using the binomial test at $P \leq .05$. Changes between successive recalls for depth of wear determined from indirect measurements were analyzed using repeated measures ANOVA at $P \leq .05$.

RESULTS

Recall levels at six months, one year, two years, three years and four years were 100 percent, 100 percent, 92 percent, 90 percent and 84 percent, respectively. Results according to USPHS criteria are summarized in Figure 1 as percentage of restorations rated alfa at recall. We detected no clinically important changes from baseline up to the four-year recall interval. Comparisons of the percentage of alfas for each recall category were not statistically significant ($P \leq .05$). We noted no restoration fractures or postoperative sensitivity. The distribution of restorations at the level of 84 percent was not markedly different at the four-year recall than it had been at baseline.

Figure 2 presents the general appearance of a representative mesio-occlusal CEREC inlay from the preoperative view through the four-year recall. Although direct examinations revealed some cement margin information, wear and other cement margin evaluations were much more accurately assessed by indirect evaluation of the casts of the restorations.

Figure 3B displays an example of the appearance of a cement margin on a stone cast in the SEM. Results of SEM analyses revealed no significant evidence of any related inlay or enamel chipping through the four-year recall interval. Furthermore, no failures resulted from cohesive fractures of the Dicor MGC ceramic material.

The adjusted means (plus or minus their standard deviations) for depths of cement loss at baseline and at each recall, in micrometers, were 0 ± 0 (baseline), 9 ± 19 (six months), 32 ± 37 (one year), 53 ± 40 (two years), 61 ± 48 (three years) and 44 ± 39 (four years) using the Leinfelder indirect evaluation method.[26] Differences between successive recalls for cement wear were significant

The direct evaluation results were extremely positive. No clinically detectable changes were noteworthy.

($P \leq .01$) for all but the two-year to three-year results ($P = .07$). These results are plotted vs. time of intraoral service in Figure 4B. The total wear measured at four years was less than that measured as late as three years. A potential explanation for this result is offered in the following discussion.

DISCUSSION

The direct evaluation results were extremely positive. No clinically detectable changes were noteworthy. In addition, no postoperative sensitivity was noted at any evaluation time (Figure 1). This observation was most encouraging and was almost unheard-of for other resin-bonded restorations. Steinberg and Matsson also reported no postoperative sensitivity using cast Dicor inlays cemented with Fuji I glass ionomer cement.[27] However, Sjögren and colleagues noted 10 of 72 patients with postoperative sensitivity when using Vita Mark I or II (Vident) CEREC inlays.[28] The finding in the current study most likely was due to the low polymerization shrinkage of the minimal thickness of resin bonding medium or resin cement and the desensitizing effect of the dentin bonding agent, Gluma,[29] which contains 5 percent glutaraldehyde.

Up to this point, we have detected change in CEREC inlays only by an indirect evaluation technique. Earlier recalls[30] already had revealed small changes at the margins resulting from relatively minor resin cement wear. That wear was not expected to create any significant clinical problems, but its consequence was unknown and was a primary reason for the extended recalls.

Leinfelder suggested that cement wear in all likelihood would continue until the depth of cement loss was equivalent to one-half the width of the marginal width (Figure 3C).[31-33] The extent of wear was hypothesized by Bayne and colleagues to be limited by the sheltering effect of the inlay and enamel surfaces.[34] Laboratory and indirect clinical analyses have reported a wide range of cement margin widths (from 80 to about 150 micrometers).[31,35,36] In earlier work at the University of North Carolina, the average occlusal cement margin width was measured as 89 ± 65 µm, suggesting that cement wear should be limited to about 40 to 50 μm.[35] Table 2 summarizes all of the published studies of CEREC involving in vitro or in vivo analyses of margins. In the table, measured values of gap width and/or cement loss depth are indicated if they were measured. Gap widths vary widely depending on many factors, including measurement site and measurement orientation.[37] Cement losses that we found involve a much narrower range (Table 2). The cement loss uncovered in our study is as low as any reported to date.

> The cement loss uncovered in our study is as low as any reported to date.

Early in the study, we questioned whether continuing cement wear would encourage marginal staining or increase the risk of the inlay margins' chipping along the occlusal surface. However, neither of these seemed to occur clinically. The SEM photograph in Figure 3B provides some evidence that the cement wear was not accompanied by significant wear or chipping of either the enamel or the inlay edges along the margin. This edge resistance was contrary to in vitro work by Krejci and colleagues[38] (1994) and O'Neal and colleagues,[32] in which these researchers observed some deterioration at those boundaries associated with cement loss. However, it may be that the deterioration observed in the laboratory studies during high-impact fatigue simulations did not accurately reflect or predict clinical changes. A more subtle rounding of the margins may occur clinically due to low stress wear phenomena. Further evaluation over time will determine the ultimate curve configuration.

Leinfelder's hypothesis (Figure 3C) that the depth of cement wear would not exceed the width of the cement margin is logical. Thus far, however, there has been no long-term proof of this pattern.

Figure 4A is a graphic analysis of average cement wear vs. time for this current study from baseline up to three years only. Two curves are fit to the experimental points. Both had very good curve fits as evidenced by the r^2 values: the logarithmic regression fit was $r^2 = .99$, while the linear regression analysis fit was $r^2 = .94$.

Graphical analysis revealed that the events associated with wear are more complex than once thought. For the data from baseline to three years (Figure 4A), both a linear and an exponential curve fit the data extremely well. That analysis left open the question of whether the cement would continue to wear at a modest rate (linear fit) or decrease to a very low rate (exponential fit) as Leinfelder had predicted.

A real surprise was revealed at four years (Figure 4B), when the total measurable wear appeared to be only about 60 percent of the earlier three-year value. Inspection of the enamel margins (Figure 3) revealed little enamel wear but perhaps enough to conceal the true extent of cement wear. This observation may be partly explained by Bayne and colleagues' work on the basis of the wear measuring method.[39] An added complication was that the enamel margin, which was the reference point for making the measurement, was itself undergoing wear. From a clinical point of view, wear of the enamel and inlay have the effect of broadening the margin, making the change at the margin appear more gradual and hiding the true wear (Figure 4C). Therefore, although wear was continuing to occur, its detectability was actually decreasing.

A similar event has been described for margin analyses of worn composite restorations.[39] The actual standard casts used to assess margins also must include worn margins; otherwise, the actual wear will be underreported.[40,41] M-L standards for wear measurement are particularly prone to this error. For this reason, Leinfelder's estimates of the actual, self-limiting depth-to-width ratio for cement margin may have been too small.[31-33] Despite this problem, there does not appear to be any significant clinical risk associated with cement wear over the short term. It may require five to 10 years for the margins to become noticeably detectable due to attrition of the cement from abrasive effects of food boluses.

This complex combination of events might not always occur as close to an equilibrium as observed in this study. In restored sites with much greater original cement widths, the cement could wear more quickly and produce greater risk of enamel or ceramic inlay chipping. For that reason, it is important that dentists pay more attention to using wear-resistant luting cements. Ujigo and colleagues demonstrated with in vitro studies that cements with higher filler content (greater than 70 percent by volume) showed better resistance to wear.[42] Essig and colleagues concluded from in vitro work that cements filled with submicrometer particles are more abrasion-resistant than hybrid composite cements.[43]

In our clinical study, we used Dual Cement (Ivoclar Vivadent) because it was a homogeneous microfill, similar in composition to Heliomolar (Ivoclar Vivadent), which has consistently shown superior wear resistance in clinical and laboratory trials.[44,45] In addition, we hypothesize that materials with low-elastic moduli allow greater cuspal flexure in hopes of providing better protection for the bonded interfaces. This consideration has been particularly important in light of the inlay's inherent rigidity and the presence of cuspal flexure during occlusal function. Ultimately, the keys to minimizing cement wear appear to be selecting a wear-resistant cement and fabricating an inlay with a very small marginal gap. Both of these features have been included in newer CEREC systems. The superior software of the CEREC Operating System Version 1.0 and higher—in combination with an electric milling machine (CEREC "E" model)—produces a smaller initial margin gap. Bonded ceramic inlays produced with Dicor MGC by the CEREC method appear to offer an excellent conservative esthetic alternative to dental amalgam or to direct composite resin restorations.

Composite resin restorations undergo wear by several mechanisms but almost universally manifest the wear at the margins, where an enamel ledge is continually exposed. The values for composite wear in clinical studies recently were summarized for more than 30 materials by pooling results of different investigators.[46] Newer wear-resistant materials have demonstrated less than 20 μm of loss per year.[47] In that respect, the wear of composite resin restorations and composite resin cements is very similar. However, composite resin restorations are not nearly as wear-resistant as bonded ceramic inlays, particularly in areas of heavy occlusal stress.

The wear reported for posterior composites and bonded inlays in any clinical study is an average of many restoration values, which are themselves an average of many variations in wear along the margins of each restoration. The extent of cement wear for inlay restorations depends largely on its orientation toward the particular abrading material (such as food). For those cases in which food is extruded across the margin, the cement wear should be lower due to protection by the walls of the enamel and inlay.[34] However, in the case in which food is extruded parallel to the margin, the wear may proceed to a much greater extent. This deterioration could lead to significant marginal staining. These types of variations in wear patterns are being monitored with selective SEM analyses of replicas of restoration surfaces.

Composite resin restorations are not nearly as wear-resistant as bonded ceramic inlays, particularly in areas of heavy occlusal stress.

It is interesting to contrast the amount of cement wear being observed with CAD-CAM restorations with occlusal wear observed for posterior amalgam or composite resin restorations. Amalgam restorations have been reported to wear about 8 to 10 μm per year.[48] Composite resin restorations placed during the 1980s typically wore 25 to 50 μm per year[49, 50] but decreased in rate of wear from the third to fifth year.[18] More wear-resistant composite resin restorations are reported to wear from 5 to 20 μm per year.[47] For the current study, the wear rate of the composite resin cement through the third year was about 20 μm per year. One might surmise that wear-resistant composite resin formulations that perform well on completely exposed occlusal surfaces might perform better than the current microfill cements that are in a more protected environment. However, even if the wear rate is lowered for luting materials, wear will not cease totally. It will simply take longer to experience the same extent of wear. While this postponement is desirable clinically, it does not solve the overall problem.

Research on more wear-resistant luting materials should examine the same factors that seem to be important for the wear resistance of composite resin filling materials. For the moment, the laboratory property with the strongest relationship to clinical wear performance seems to be toughness. Toughness is a measure of a material's resistance to crack propagation. Results of a round-robin testing exercise conducted by the ADA demonstrated a modest correlation with in vitro wear simulation outcomes.[51]

Wear resistance of enamel and the inlay material are also of critical importance in this restoration assembly. Enamel normally demonstrates excellent wear resistance except in situations such as this one, where it is not adequately supported and is subject to greater wear. Dicor MGC demonstrates excellent bulk wear resistance but is subject to the same problems as enamel. A more wear-resistant luting cement would postpone wear and dramatically improve long-term performance. A summary of clinical in vitro studies of cement wear and gap width[52-64] are noted in Table 2.

The ceramic inlays in this study appeared to be clinically acceptable after four years of service with little cement wear and no clinical failures. However, no research has yet provided an absolute definition of just how accurate the marginal fit must be for clinical success for bonded restorations of this type. While the current CEREC equipment can produce inlays that surpass the fit encountered in this study, other equipment also may do as well. Newer copy milling approaches may be equally successful using the same inlay and cement materials.

SUMMARY AND CONCLUSIONS

Fifty CEREC inlay restorations were placed originally for evaluation. We examined 42 restorations (84 percent) at recall visits after four years. All restorations were clinically acceptable and no failures had occurred. In spite of some detectable cement loss at the margins, the clinical appearance and integrity of CEREC computer-generated ceramic inlays made from Dicor MGC and cemented with a homogeneous microfill cement appeared excellent after four years of service.

The unusual decrease in measured cement wear total from the third to fourth year was explained in terms of the simultaneous wear of the enamel margin, thus changing the reference point for the measurement. On the basis of our findings, we propose that cement wear is self-limiting, but not entirely in the same manner previously hypothesized by Leinfelder.[31-33] ■

Portions of this work were originally presented at the 21st annual meeting of the American Association for Dental Research in Boston in March 1992. This research was supported in part by Pelton and Crane, Siemens Dental, Charlotte, N.C. None of the investigators has received any direct or indirect compensation on behalf of any of the materials or research activities identified in this article.

Dr. Heymann is professor and chair, Department of Operative Dentistry, School of Dentistry, University of North Carolina, Chapel Hill, N.C. 27500-7450. Address reprint requests to Dr Heymann.

Dr. Bayne is professor, Department of Operative Dentistry, School of Dentistry, University of North Carolina, Chapel Hill, N.C.

Dr. Sturdevant is associate professor, Department of Operative Dentistry, School of Dentistry, University of North Carolina, Chapel Hill, N.C.

Dr. Wilder is associate professor, Department of Operative Dentistry, School of Dentistry, University of North Carolina, Chapel Hill, N.C.

Dr. Roberson is professor, Department of Operative Dentistry, School of Dentistry, University of North Carolina, Chapel Hill, N.C.

1. Duret F, Blouin JL, Nahmani L. Principes de fonctionnement et applications techniques de l'empreinte optique dans l'exercise de cabinet. [Functional principles and technical applications of optical impressions in office practice.] Cah Prothese 1985;13(50):73-110.
2. Duret F, Blouin JL, Duret B. CAD-CAM in dentistry. JADA 1988;117:115-20.
3. Moermann WH, Brandestini M, Ferru A, Lutz F. Computer machined adhesive porcelain inlays: margin adaptation after fatigue stress (Abstract no. 339). J Dent Res 1986;65:763.
4. Moermann WH, Brandestini M. Method and apparatus for the fabrication of custom-shaped implants. U.S. patent no. 4575805, March 11, 1986. Washington, D.C.: U.S. Patent office.
5. Moermann WH, Brandestini M. CEREC tutorial step by step. [Technical manual.] University of Zurich, Dental Institute, 1988.
6. Brandestini M, Moermann WH, Lutz F, Krejci I. Computer machined ceramic inlays: in vitro marginal adaptation (Abstract no. 305). J Dent Res 1985,64:208.
7. Brandestini M, Moermann WH. Computerized processing of ceramic fillings in the dental operatory. [Technical manual.] Bensheim, West Germany: Siemens AG, Dental Sector; 1988.
8. Moermann WH, Lutz F, Goetsch T. CAD-CAM ceramic inlays and onlays: a case report after three years in place. JADA 1990;120(5):517-20.
9. Rekow ED, Speidel TM, Erdman AG. Computer-aided system to automate production of posterior dental restorations (Abstract no. 1336). J Dent Res 1986;65:317.
10. Rekow ED. Computer-aided design and manufacturing in dentistry: A review of the state of the art. J Prosthet Dent 1987;58:512-6.
11. Rekow ED. Dental CAD-CAM systems. What is the state of the art? JADA 1991;122(13):43-8.
12. Karlsson S. The fit of Procera titanium crowns. An in vitro and clinical study. Acta Odontol Scand 1993;51(3):129-34.
13. Van der Zel JM. Ceramic-fused-to-metal restorations with a new CAD-CAM system. Quintessence Int 1993;24:769-78.
14. Mikrona Dentaltechnik. CELAY technical bulletin. Munich: Mikrona Dentaltechnik; 1993.
15. Andersson M, Bergman B, Bessing C, Ericson G, Lundquist P, Nilson H. Clinical results with titanium crowns fabricated with machine duplication and spark erosion. Acta Odontol Scand 1989;47(5):279-86.
16. Bergman B, Bessing C, Ericson G,

Lundquist P, Nilson H, Andersson M. A two-year follow-up study of titanium crowns. Acta Odontol Scand 1990;48(2):113-7.
17. Dudek R. The PROCERA system for machining titanium restorations. In. Conference proceedings, Dental materials: preparing for the next one hundred years. Chicago: Northwestern University Dental School; 1991:12.
18. Sturdevant JR, Lundeen TF, Sluder TB Jr., Leinfelder KF. Three-year study of two light-cured posterior composite resins. Dent Mater 1986;2(6):263-8.
19. Brunson WD, Bayne SC, Sturdevant JR, Roberson TM, Wilder AD, Taylor DF. Three-year clinical evaluation of a self-cured posterior composite resin. Dent Mater 1989;5(2):127-32.
20. Wilder AD, Bayne SC, May KN, Leinfelder KF, Taylor DF. Five-year clinical study of u.v.-polymerized posterior composites. J Dent 1991;19(4):214-20.
21. Siemens AG. CEREC operating instructions. Bensheim, W. Germany: Siemens Aktiengesellschaft; 1988.
22. Heymann HO. CAD-CAM for ceramic inlays and onlays: the CEREC system. Trans Acad Dent Mater 1989;2:8-16.
23. Haywood VB, Heymann HO, Kusy RP, Whitley JQ, Andreaus SB. Polishing porcelain veneers: an SEM and specular reflectance analysis. Dent Mater 1988;4(3):116-21.
24. Haywood VB, Heymann HO, Scurria MS. Effects of water, speed, and experimental instrumentation on finishing and polishing porcelain intraorally. Dent Mater 1989;5:185-8.
25. Heymann HO, Sturdevant JR, Brunson WD, Wilder AD, Sluder TB, Bayne SC. Twelve month clinical study of dentinal adhesives in class V cervical lesions. JADA 1988;116:179-83.
26. Leinfelder KF, Taylor DF, Barkmeier WW, Goldberg AJ. Quantitative wear measurement of posterior composite resins. Dent Mater 1986;2(5):198-201.
27. Stenberg R, Matsson L. Clinical evaluation of glass ceramic inlays (Dicor). Acta Odontol Scand 1993,51(2):91-7.
28. Sjögren G, Bergman M, Molin M, Bessing C. A clinical examination of ceramic (CEREC) inlays. Acta Odontol Scand 1992;50(3):171-8.
29. Felton DA, Bergenholtz G, Kanoy BE. Evaluation of the desensitizing effect of Gluma Dentin Bond on teeth prepared for complete-coverage restorations. Int J Prosthodont 1991;4(3):292-8.
30. Heymann HO, Wilder AD, Sturdevant JR, Roberson TM, Bayne SC. Two-year clinical performance of CEREC CAD-CAM generated MGC inlays (Abstract no. 814). J Dent Res 1992;71:207.
31. Isenberg BP, Essig ME, Leinfelder KF. Three-year clinical evaluation of CAD-CAM restorations. J Esthet Dent 1992;4(5):173-6.
32. O'Neal SJ, Miracle RL, Leinfelder KF. Evaluating interfacial gaps for esthetic inlays. JADA 1993;124(12):48-54.
33. Kawai K, Isenberg BP, Leinfelder KF. Effect of gap dimension on composite resin cement wear. Quintessence Int 1994;25(1):53-8.
34. Bayne SC, Taylor DF, Heymann HO. Protection hypothesis for composite wear. Dent Mater 1992;8(5):305-9.
35. Sturdevant JR, Heymann HO, Wilder AD, Roberson TM, Bayne SC. Composite cement thickness of CEREC CAD-CAM ceramic inlays (Abstract no. 245). J Dent Res 1991;70:296.
36. Moermann WH. Chairside computer-generated ceramic restorations: the CEREC third generation improvements. Pract Periodontics Aesthet Dent 1992;4(7):9-16.
37. Holmes JR, Bayne SC, Holland GA, Sulik WD. Considerations in measurement of marginal fit. J Prosthet Dent 1989;62(4):405-8.
38. Krejci I, Lutz F, Reimer M. Wear of CAD-CAM ceramic inlays: restorations, opposing cusps, and luting cements. Quintessence Int 1994;25(3):199-207.
39. Bayne SC, Taylor DF, Rekow ED, Wilder AD, Heymann HO. Confirmation of Leinfelder clinical wear standards. Dent Mater 1994;10(1):11-8.
40. Taylor DF, Bayne SC, Sturdevant JR, Wilder AD. Comparison of direct and indirect methods for analyzing wear of posterior composite restorations. Dent Mater 1989;5(3):157-60.
41. Taylor DF, Bayne SC, Sturdevant JR, Wilder AD. Correlation of M-L, Leinfelder, and USPHS clinical evaluation techniques for wear. Dent Mater 1990;6(3):151-3.
42. Ujigo Y, Torii Y, Inoue K. Filler content versus wear of resin cement around CAD-CAM inlays (Abstract no. 1787). J Dent Res 1994;73:325.
43. Essig ME, Isenberg BP, Leinfelder KF, Mueninghoff LA. An in-vivo evaluation of Duo-Cured cements with CAD-CAM ceramic inlays (Abstract no. 244). J Dent Res 1991;70(A):296.
44. Moermann W, Krejci I. Computer-designed inlays after 5 years in situ: clinical performance and scanning electron microscopic evaluation. Quintessence Int 1992;23(12):109-15.
45. Frazier KB, Sarrett DC. Wear resistance of dual-cured resin luting agents. Am J Dent 1995;8(4):161-4.
46. Taylor DF, Bayne SC, Leinfelder KF, Davis S, Koch GG. Pooling of long-term clinical wear data for posterior composites. Am J Dent 1994;7(3):167-74.
47. Leinfelder KF. Posterior composite resins: the materials and their clinical performance.JADA 1995;126:663-76.
48. Lutz F, Phillips RW, Roulet JF, Setcos JC. In vivo and in vitro wear of potential posterior composites. J Dent Res 1984;63:914-20.
49. Leinfelder KF. Wear patterns and rates of posterior composite resins. Int Dent J 1987;37(3):152-7.
50. Leinfelder KF, Wilder AD, Teixeira LC. Wear rates of posterior composite resins. JADA 1986;112:829-33.
51. Bayne SC, Leinfelder KF, Taylor DF. Agreement of in vivo and in vitro composite wear results (Abstract no. 4). Trans of Acad Dent Mater 1992;5(3):109-10.
52. Gladys S, Van Meerbeek B, Inokoshi S, et al. Clinical and semiquantitative marginal analysis of four tooth-coloured inlay systems at three years. J Dent 1995;23(6):329-38.
53. Goetsch T, Moermann W, Krejci I, Lutz F. Cerec ceramic inlays clinically assessed using modified USPHS criteria (Abstract no. 425). J Dent Res 1990;69:162.
54. Zuellig R, Bryant R. Two year evaluation of Cerec restorations: influence of luting agent (Abstract no. 34). J Dent Res 1995;74:405.
55. Thordrup M, Isidor F, Horsted-Bindslev P. A one-year clinical study of indirect and direct composite and ceramic inlays. Scand J Dent Res 1994;102(3):186-92.
56. Isenberg BP, Essig ME, Leinfelder KF. Clinical evaluation of CEREC CAD-CAM restorations emphasizing marginal integrity (Abstract no. 1346). J Dent Res 1991;70:434.
57. Sjögren G. Marginal and internal fit of four different types of ceramic inlays after luting. An in vitro study. Acta Odontol Scand 1995;53(1):24-8.
58. Krejci I, Lutz F, Reimer M. Marginal adaptation and fit of adhesive ceramic inlays. J Dent 1993;21(1):39-46.
59. Fett HP, Moermann WH, Krejci I, Lutz F. The effects of short bevels and silanization on marginal adaptation of computer-machined mesio-occlusodistal inlays. Quintessence Int 1991;22:823-9.
60. Thordrup M, Isidor F, Horsted-Bindslev P. Comparison of the marginal fit and microleakage of ceramic and composite inlays: an in vitro study. J Dent 1994;22(3):147-53.
61. Siervo S, Pampalone A, Siervo P, Siervo R. Where is the gap? Machinable ceramic systems and conventional laboratory restorations at a glance. Quintessence Int 1994;25(11):773-9.
62. Molin M, Karlsson S. The fit of gold inlays and three ceramic inlay systems. A clinical and in vitro study Acta Odontol Scand 1993;51(4):201-6.
63. Hembree JH Jr. Comparisons of fit of CAD-CAM restorations using three imaging surfaces. Quintessence Int 1995;26(12):145-7.
64. Inokoshi S, Van Meerbeek B, Willems G, Lambrechts P, Braem M, Vanherle G. Marginal accuracy of CAD-CAM inlays made with the original and the updated software. J Dent 1992;20(3):171-7.

Marginal adaptation and fit of adhesive ceramic inlays

I. Krejci, F. Lutz and M. Reimer
Department of Preventive Dentistry, Periodontology and Cariology, Dental Institute, Zurich University, Switzerland

ABSTRACT

This *in vitro* study compared the marginal adaptation of CAD/CAM and laboratory-made ceramic inlays before, during and after loading. Six MOD inlay preparations of standardized design with one cervical margin in dentine and the other in enamel were prepared for each inlay type: CAD/CAM fabricated MGC-glass ceramic inlays, CAD/CAM fabricated feldspathic porcelain inlays, laboratory-made glass ceramic inlays and laboratory-made feldspathic porcelain inlays. Appropriate luting composite materials were used. The restored teeth were subjected to occlusal loading, thermal cycling, toothbrush–toothpaste abrasion and chemical degradation *in vitro*. Marginal adaptation was quantitated along the entire length of the cavosurface margin and along selected sections of the margin using SEM, following *in vitro* testing corresponding to 0, 0.5, 1.0, 2.7 and 5.0 years of clinical service. In addition, marginal fit of the cemented inlays was evaluated in the SEM. The initial marginal adaptation in enamel was excellent in all groups. After *in vitro* testing, significant marginal discrepancies were found in all groups. A high percentage of marginal openings was recorded, notably in the cervical portions of the margins in both enamel and dentine.

KEY WORDS: Inlays, Ceramic, Marginal adaptation, Marginal fit

J. Dent. 1993; **21**: 39–46 (Received 10 March 1992; reviewed 30 April 1992; accepted 4 September 1992)

Correspondence should be addressed to: Priv. Doz. Dr I. Krejci, Dental Institute, PDM PER CAR, Plattenstr. 11, CH-8028, Zurich, Switzerland.

INTRODUCTION

The first descriptions of ceramic inlays date back to the beginning of this century (Peck, 1902; Byram, 1908). At that time, the main application for a ceramic inlay was the Class V restoration, because the porcelain used then was of low strength and was cemented with zinc phosphate cement. Such a restorative system was too weak for the occlusal loads in posterior teeth. In addition, the ceramic fabrication technique was very difficult, time consuming and often inaccurate. However, the advent of bonding techniques, using composite luting materials, the development of new ceramic materials and more accurate fabrication methods enabled ceramics to be used as posterior restorations (Adair and Grossman, 1984; Grossman, 1985; Mörmann and Brandestini, 1989). Ceramic inlays are currently being increasingly promoted as tooth-coloured amalgam alternatives. Two main fabrication methods are in use: the CAD/CAM procedure, which generates ceramic inlays in the dental office within one appointment, and a more conventional indirect procedure, requiring an impression and two appointments. In both cases, porcelain or glass ceramic may be used as the restorative material.

Little long-term quantitative data is available on the behaviour of adhesive ceramic inlays. Besides wear resistance, the main point of interest is the prediction of the quality and stability of the marginal adaptation of such restorations. Therefore the purpose of this study was to quantify the marginal adaptation and marginal fit of CAD/CAM and laboratory-made ceramic inlays, fabricated from different ceramic materials and bonded in extracted lower human molars in a long-term, clinically correlated *in vitro* test.

MATERIALS AND METHODS

Twenty-four sound caries-free first lower human molars of similar size and shape were selected for the study and

Table I. Characterization of the experimental groups

	Group			
	1	2	3	4
Inlay				
Material	Dicor	Dicor MGC	Biodent	CEREC Vita Mk I
Classification	Glass ceramic	Glass ceramic	Porcelain	Porcelain
Manufacturing technique	Laboratory made	CAD/CAM	Laboratory made	CAD/CAM
Manufacturer	Dentsply	Dentsply	Dentsply	Vita
Composite cement				
Material	DC Inlay Cement	DC Inlay Cement	DC Inlay Cement	Duo Cement
Classification	Fine hybrid	Fine hybrid	Fine hybrid	Fine hybrid
Curing mode	Dual cured	Dual cured	Dual cured	Dual cured
Manufacturer	Dentsply	Dentsply	Dentsply	Coltène

Table II. Criteria for the quantitative evaluation of the marginal adaptation in the SEM

Interface	*Tooth/cement*	*Cement/inlay*
CM	Continuous margin	Continuous margin
MG	Marginal gap	Marginal gap
MTF	Marginal tooth fracture	—
MCF	Marginal cement fracture	Marginal cement fracture
MIF	—	Marginal inlay fracture
OM	Overfilled margin	Overfilled margin
UM	Underfilled margin	Underfilled margin

cleaned using a rubber cup and a fine pumice water slurry. Each tooth was fixed in the centre of custom-made specimen holders using cold cure acrylic (Paladur, Kulzer GmbH, Friedrichsdorf, Germany). The mounted teeth were divided at random into four equal groups as described in *Table I*. Box-shaped *non-bevelled* Class II cavities of standardized shape and dimensions (Krejci, 1992) were prepared using 80 μm diamond burs and finished using 25 μm diamond burs (Universal Prep Set, Intensiv SA, Lugano-Viganello, Switzerland) (Reller *et al.*, 1989). The cavities had a length of 10.0 mm in the mesiodistal direction and a width of 5.0 mm in the central fissure. They were 3.2 mm, 5.4mm and 6.5mm deep in the occlusal, mesioproximal and distoproximal boxes respectively. For the laboratory-made inlays in groups 1 and 3, an occlusal divergence of 4° was considered appropriate for the cavity. In accordance with the CEREC procedure (Mörmann and Brandestini, 1989), parallel walls in the occlusal box and a 4° divergence in the proximal areas were prepared in groups 2 and 4. The cervical margin of the mesial box of each preparation was placed 1 mm above the amelocemental junction. The margin of the distoproximal box was located in dentine. The preparations were assessed using ×25 magnification in a stereomicroscope (M5A, Wild AG, Heerbrugg, Switzerland), ensuring that only sharp, fracture-free margins were present. No base was applied to avoid bias (Bronwasser *et al.*, 1991).

In groups 1 and 3, the cavities were replicated using a polyvinylsiloxane impression material (Reprosil, DeTrey/Dentsply, Dreieich, Germany) and fabricated according to the manufacturer's instructions without a glaze. In groups 2 and 4, CAD/CAM inlays were machined in the CEREC machine with Software Version 1.0 (Siemens, Bensheim, Germany) using CEREC MGC and CEREC Vita Mk I ceramic blocks respectively. In all groups the enamel margins of the preparations were etched with 37% phosphoric acid gel for 30 s. The inlays of groups 1 and 2 were etched for 30 s using Dicor Etch Gel (DeTrey/Dentsply, Dreieich, Germany), which is a 10% ammonium-bifluoride solution. The inlays of groups 3 and 4 were etched for 120 s using Strip-It (National Keystone Products Co. Philadelphia, USA), which is a mixture of hydrofluoric acid and sulphuric acid. Finally, the inlays were silanized using Silane Primer & Activator (DeTrey/Dentsply, Dreieich, Germany) in groups 1, 2 and 3 and Silicoup (Heraeus-Kulzer & Co. GmbH, Friedrichsdorf, Germany) in group 4. Before placement, the preparations and the inlays were covered with a thin layer of a non-functional bonding agent. Dual cured resin composite luting materials were used for bonding (*Table I*). They were light cured (Translux CL, Heraeus-Kulzer & Co. GmbH, Friedrichsdorf, Germany) from the cervical region using laterally reflecting wedges (Luciwedge, Hawe Neos, Lugano-Gentillino, Switzerland) and from the buccal, lingual and occlusal surfaces for 60 s each. Occlusal contouring of the CAD/CAM inlays was completed using fine diamonds (Composhape Set, Intensiv SA, Lugano-Viganello, Switzerland), Superfine diamond burs (Composhape Set) were used for the removal of excess composite luting material in all groups. Finally, the inlays were finished using fine and superfine flexible discs (SofLex, 3M, St Paul, MN, USA).

Immediately after finishing, replicas made from

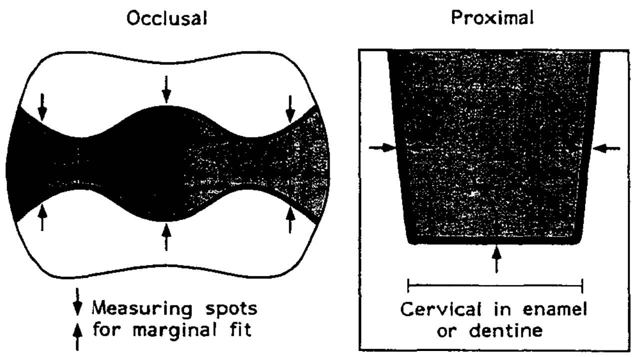

Fig. 1. Schematic representation of the marginal sections of an MOD inlay, which were rated separately in the scanning electron microscope. In addition, the measuring spots for marginal fit are depicted.

impressions of a polyvinylsiloxane system (President Light Body, Coltène AG, Alstätten, Switzerland) were made for the quantitative marginal analyses in the SEM (Stereoscan S100, Cambridge Instruments, Dortmund, Germany). Thereafter, the restorations were subjected to a total of 5 years *in vitro* simulated *in vivo* function (Krejci and Lutz, 1990; Krejci *et al.*, 1990a, b) by exposing the restorations to the following stresses: (1) chemical disintegration (75 vol% aqueous ethanol solution, 37 °C); (2) toothbrush/toothpaste abrasion (2 N load); (3) cyclic chewing loads applied to the centre of the occlusal surfaces of the restorations (max. load 49 N; chewing frequency 1.7 Hz); and (4) simultaneous thermal cycles in flushing water (5–55 °C; 2 min dwell time, 10 s transfer time). The marginal adaptation was quantitatively assessed in the SEM at each interval using the criteria shown in *Table II*. Interval A with a total of 24 h chemical disintegration, 30 min toothbrush/toothpaste abrasion, 120000 chewing cycles and 300 thermal cycles corresponded to 6 months of clinical service; interval B with a total of 48 h chemical disintegration, 60 min toothbrush/toothpaste abrasion, 240000 chewing cycles and 600 thermal cycles corresponded to 1 year; interval C with a total of 128 h chemical disintegration, 160 min toothbrush/toothpaste abrasion, 640000 chewing cycles and 1600 thermal cycles corresponded to 2.7 years; interval D with a total of 240 h chemical disintegration, 300 min toothbrush/toothpaste abrasion, 1200000 chewing cycles and 3000 thermal cycles corresponded to approximately 5 years (Krejci and Lutz, 1990). In addition to the total marginal length, the occlusal, proximal and cervical sections of the margins were scored separately in the SEM at × 200 magnification (*Fig. 1*). Separate readings were recorded for tooth/luting composite and luting composite/inlay interfaces.

Marginal fit was defined as the interfacial distance between the luted restoration and the tooth structure. It was measured perpendicularly to the luting gap, using a digital measuring bar in the SEM. The locations of the measurements are depicted in *Fig. 1*.

The data for marginal adaptation of groups 1–4 expressed as the percentages of 'continuous margin' before and after the long-term load test were statistically evaluated using both the *T*-method and the *t*-test for paired comparisons. A 0.05 level of significance was used in all the statistical computations using the *T*-method. The data of marginal fit were evaluated using the *T*-method (Sokal and Rohlf, 1981).

RESULTS

The mean percentages of 'continuous margin' for each group before, during and after the load test at the *tooth–luting composite interface* are shown in *Figs 2–5*. The LSD (least significant differences, $P < 0.05$) in percentages for the total marginal length were ± 4.6 and ± 6.7 before and after the load test respectively. The statistical significances of percentages of 'continuous margin' amongst groups before and after the load test are summarized in *Table III*.

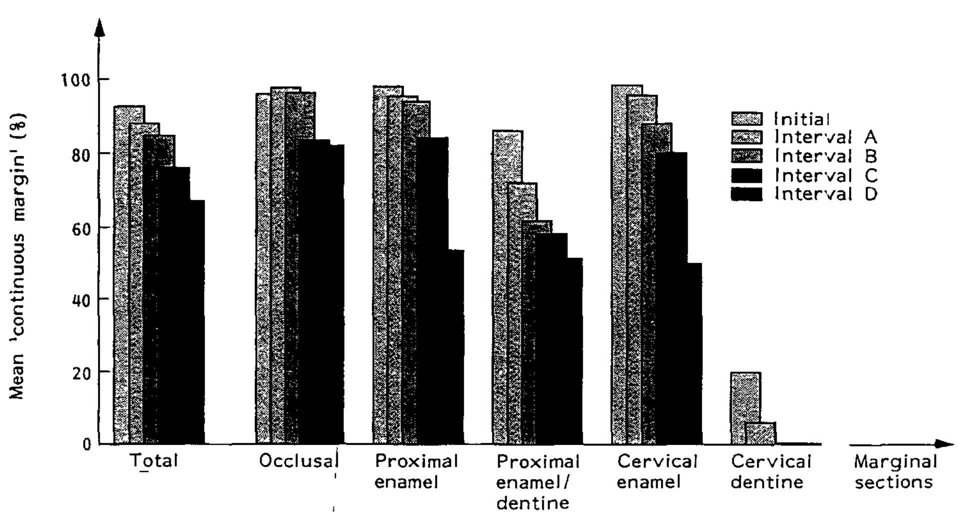

Fig. 2. Mean percentages of 'continuous margin' at the interface between tooth and cement in group 1 (Dicor, laboratory made).

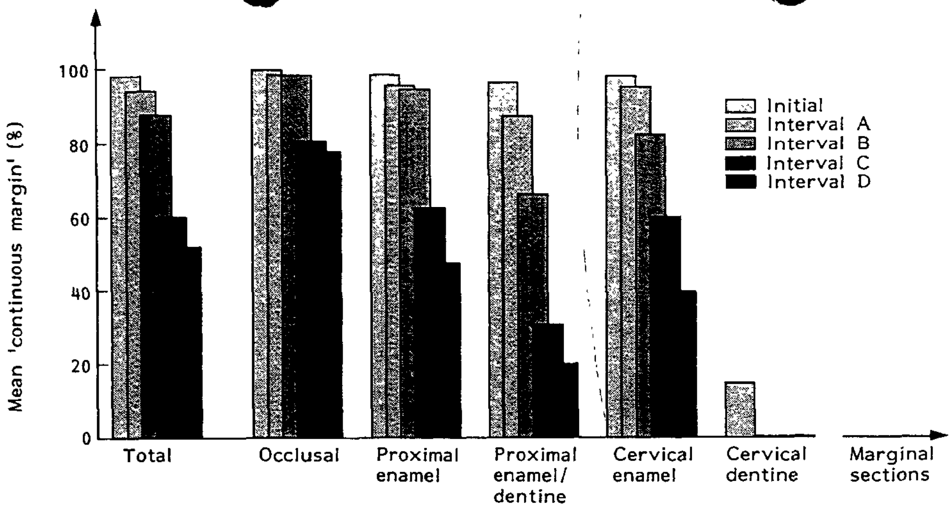

Fig. 3. Mean percentages of 'continuous margin' at the interface between tooth and cement in group 2 (Dicor MGC, CAD/CAM).

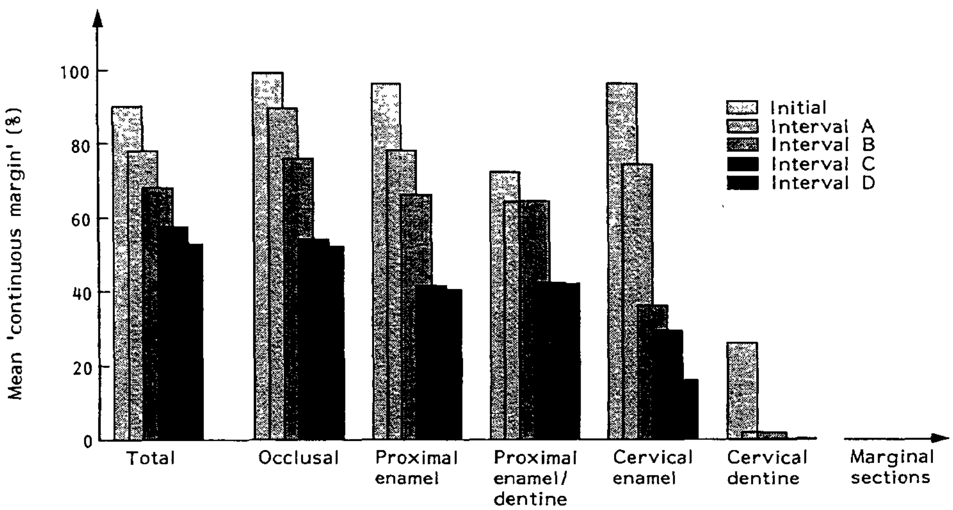

Fig. 4. Mean percentages of 'continuous margin' at the interface between tooth and cement in group 3 (Biodent, laboratory made).

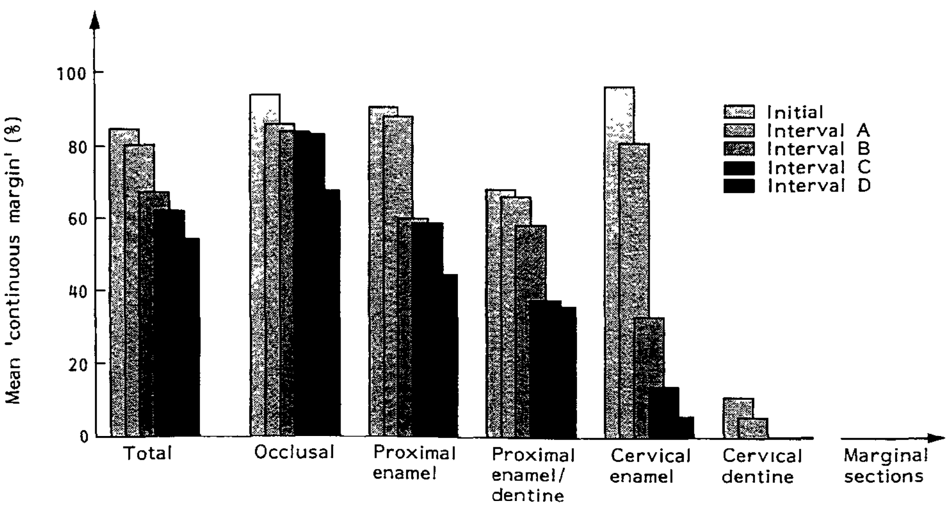

Fig. 5. Mean percentages of 'continuous margin' at the interface between tooth and cement in group 4 (CEREC Vita Mk I, CAD/CAM).

Table III. Levels of significance between percentages of 'continuous margin' among groups before/after the load test

	Group 1	Group 2	Group 3	Group 4
Interface tooth/cement				
Occlusal	*	**	***	*
Proximal with cervical margin in enamel	**	**	***	**
Cervical in enamel	**	**	***	***
Proximal with cervical margin in dentine	***	***	**	**
Cervical in dentine	***	**	**	*
Total restoration	***	***	***	***
Interface cement/inlay				
Occlusal	NS	*	NS	NS
Proximal with cervical margin in enamel	*	*	***	NS
Cervical in enamel	**	**	**	NS
Proximal with cervical margin in dentine	NS	***	***	*
Cervical in dentine	NS	*	**	NS
Total restoration	*	***	***	*

$*P < 0.05$; $**P < 0.01$; $***P < 0.001$; NS, not significant.

The mean percentages of 'continuous margin' with the appropriate LSD values for the *cement-inlay interface* over the total restoration margin length are depicted in *Fig. 6.* The percentages of 'marginal enamel fracture' initially and following the test are summarized in *Table IV.* A typical example of 'marginal enamel fractures' is shown in *Fig. 7.* At the beginning of the test, no underfilled margins were found. At the end of the long-term *in vitro* test however, the entire occlusal margins in all groups were underfilled because of abrasion of the luting composites. All other marginal qualities did not exceed 2%. Therefore these results are not presented in detail. Marginal fit of the inlays is shown in *Fig. 8.*

DISCUSSION

Quantitative marginal analysis by SEM is non-destructive, allowing consecutive measurements. In addition, different sections of the marginal area may be judged separately, allowing specific statements on the localization of marginal defects (Krejci *et al.*, 1990c). The initial percentages of continuous margin at the enamel–composite lute and composite lute–ceramic exceeded 90% in all test groups. Similar results were reported from previous clinical studies (Herder and Roulet, 1988; Bronwasser *et al.*, 1991; Krejci *et al.*, 1992; Van Meerbeek *et al.*, 1992). These results demonstrate that the initial marginal adaptation of adhesive inlays in enamel was superior to restorative systems luted with zinc phosphate or polyalkenoate cements (Brandestini *et al.*, 1985; Geppert and Roulet, 1986; Shortall *et al.*, 1989). After the first load period of the long-term *in vitro* test, relatively small changes in the marginal qualities were recorded. At the end of the long-term *in vitro* test, however, only 52–68% of the margins were continuous, indicating that long-term observations are necessary to judge the stability of marginal adaptation. Because the coefficient of thermal expansion of ceramic materials is similar to that of the tooth structure (*Table V*), and because the mass of the luting composite was minimal, the disintegrations were unlikely to have been induced by thermal cycling. This hypothesis is substantiated by other investigations, where only slight marginal disintegrations of ceramic inlays were seen when tested by thermal cycling only (Geppert and Roulet, 1986; Mörmann and Brandestini, 1989). *In vitro* load tests using thermal cycling only do not appear adequate to evaluate ceramic restorations. In addition, occlusal loading, especially on a long-term basis, must also be incorporated. The high modulus of elasticity of the presently available dental ceramic inlays (*Table V*) led to the transfer of the occlusal loads directly to the margins.

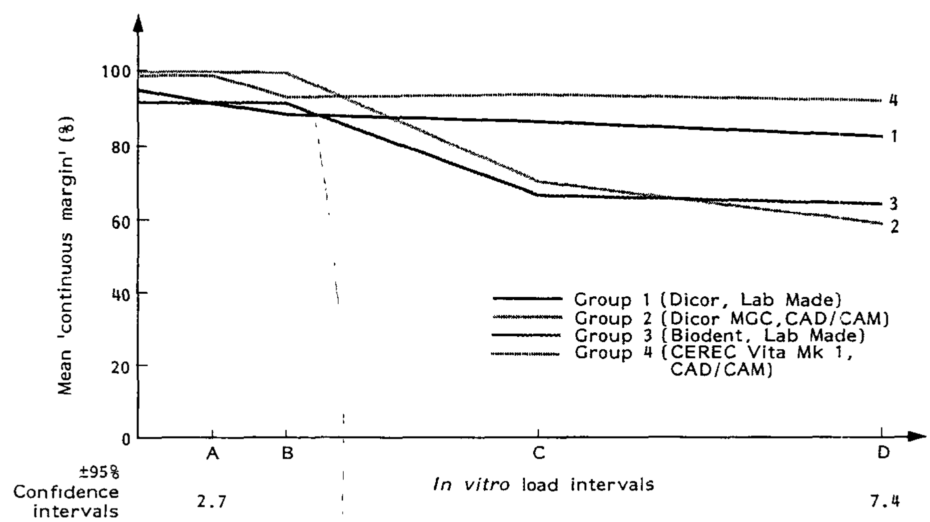

Fig. 6. Mean percentages of 'continuous margin' for the total marginal length at the interface cement/inlay in groups 1–4.

Table IV. Percentages of 'marginal enamel fracture' at the beginning and at the end of the long-term *in vitro* load test

	Group 1	Group 2	Group 3	Group 4
Occlusal				
0	0.0 ± 0.0	1.3 ± 2.1	0.0 ± 0.0	0.0 ± 0.0
IV	3.0 ± 2.2	14.5 ± 5.6	14.1 ± 5.8	13.9 ± 6.0
Proximal with cervical margin in enamel				
0	1.2 ± 3.1	2.1 ± 3.3	2.8 ± 4.1	2.2 ± 2.5
IV	21.7 ± 8.9	33.0 ± 12.5	47.3 ± 14.6	50.0 ± 18.8
Cervical in enamel				
0	1.4 ± 2.1	2.4 ± 3.1	3.2 ± 3.5	2.8 ± 1.2
IV	27.2 ± 9.2	58.4 ± 17.1	50.0 ± 15.8	88.9 ± 19.2
Proximal with cervical margin in dentine				
0	0.0 ± 0.0	2.2 ± 3.2	1.4 ± 2.0	1.1 ± 2.2
IV	9.6 ± 5.2	22.4 ± 8.1	16.3 ± 5.7	10.6 ± 4.2
Cervical in dentine				
0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
IV	0.0 ± 0.0	0.0 ± 10.0	0.0 ± 0.0	0.0 ± 0.0
Total restoration				
0	0.6 ± 2.1	1.7 ± 2.5	2.1 ± 3.1	2.2 ± 1.9
IV	9.9 ± 4.1	21.4 ± 7.6	23.8 ± 7.2	23.8 ± 8.1

This resulted in a high percentage of cohesive enamel fractures (*Table IV*). Because of the axial direction of the chewing forces and because of the fragile enamel morphology, cervical margins in particular were affected. The least disintegrations were recorded occlusally, most probably because of the flexibility of the cavity walls (Lutz *et al.*, 1991) and because occlusal enamel may be less fragile.

Without the use of dentinal adhesives, a high percentage of marginal gaps were found along the dentinal portions of the margins prior to loading in all the groups. These findings correlate well with results of previous studies (Joseph and Cohen, 1988; Tjan *et al.*, 1989). The reduction of the shrinking composite mass *in situ*, attained by the inlay principle, is insufficient to eliminate shrinkage completely. Therefore the use of efficient dentinal adhesive remains indispensible (Davidson *et al.*, 1984; Bronwasser *et al.*, 1991).

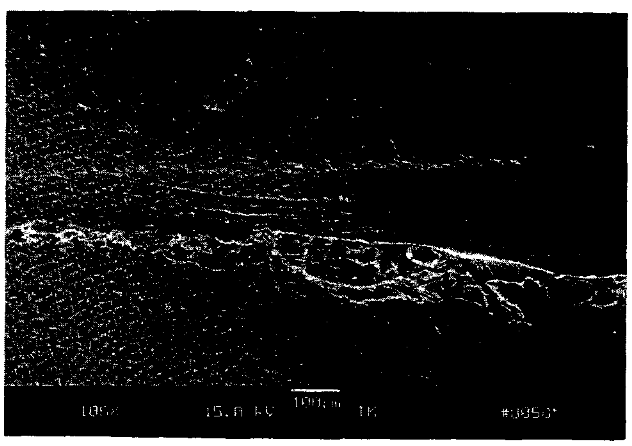

Fig. 7. Enamel fractures at the certical margin of a ceramic inlay of group 4 at the end of the *in vitro* load test (SEM, × 73).

Initially the interphase composite lute-ceramic was excellent. The adhesion mediated by the acid-etch technique in conjunction with silanization proved sufficient for excellent *initial* marginal adaptation. However, this interface disintegrated after loading, especially in groups 2 and 3. It is concluded that the pretreatment methods of the ceramic surfaces were not ideal in these two groups (Van Meerbeek *et al.*, 1992). Consequently, specific pretreatment methods may be necessary for each ceramic inlay system.

Marginal fit was significantly lower with the CAD/CAM system than with the laboratory-made groups. Exact fitting CEREC inlay margins were observed only along the cervical portions in enamel, most probably due to the manual adjustment, which allowed some inlays to contact the cervical margins of one proximal box. The marginal fit of the laboratory-made inlays was good along the entire margin, which reflected the high standard of the manufacturing techniques used. For conventional gold inlays and crowns, a marginal fit of less than 50 µm has been advocated in the literature (Dreyer-Jørgensen, 1958). However, this value is not obtained routinely in the clinic (Diedrich and Erpenstein, 1985) and assumes cementation with a zinc phosphate cement. In this investigation involving adhesively luted inlays, the quality of marginal adaptation did not seem to depend on marginal fit. These findings substantiated the results of an earlier study, in which marginal fit of up to 200 µm was judged not to be critical for the marginal adaptation of adhesive inlays (Lutz *et al.*, 1991).

CONCLUSIONS

The ceramic inlays tested in this study showed excellent initial marginal adaptation in enamel regardless of the

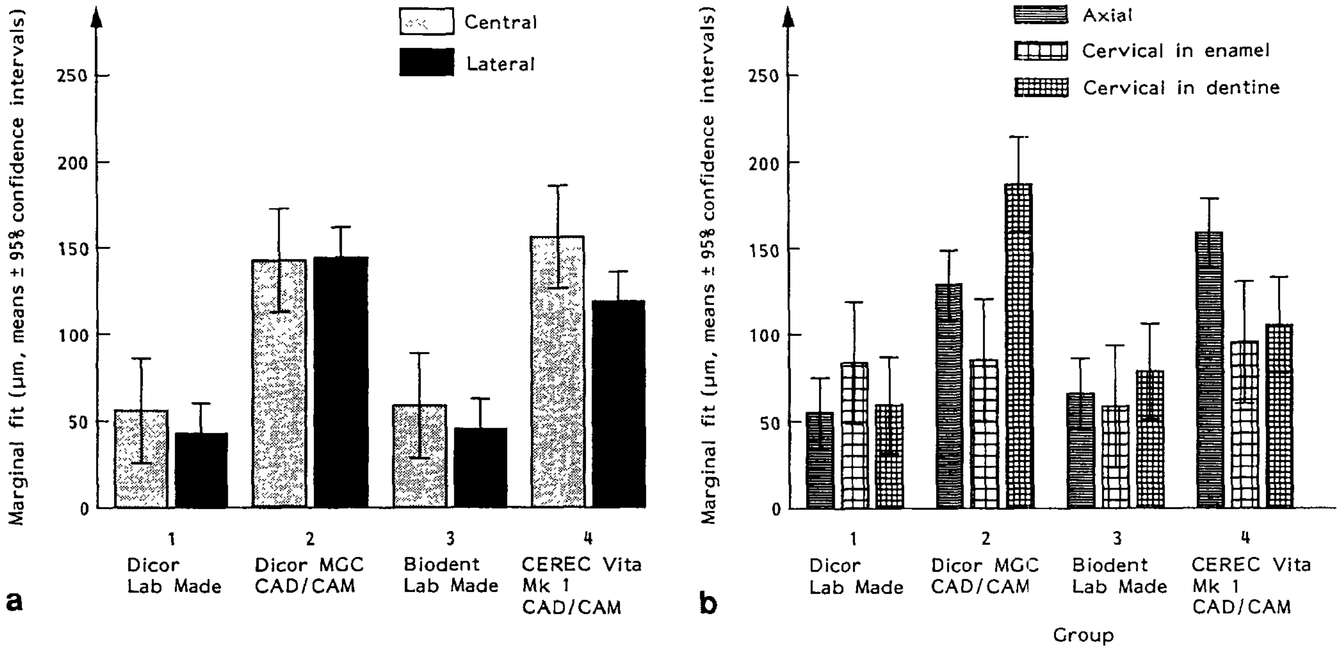

Fig. 8. Marginal fit of the ceramic inlays. *a,* Occlusal readings. *b,* Proximal readings.

Table V. Modulus of elasticity and coefficient of thermal expansion of ceramic materials compared to dentin and enamel (Adair and Grossman, 1984)

	Modulus of elasticity (GPa)	*Coefficient of thermal expansion ($\times 10^{-6}/°C$)*
Glass ceramic	70.3	7.2
Porcelain	69.0	12.0
Enamel	84.1	11.4
Dentine	18.3	—
Composite	16.3	26–40

fabrication technique used. However, no dentinal sealing was possible without the use of dentinal adhesives. Combined thermal, mechanical and chemical testing caused disintegration of the marginal adaptation of ceramic inlays, irrespective of marginal fit. As bevelling of the enamel margins does not prevent these problems (Qualtrough *et al.*, 1991; Schibli, 1991), ceramics with a modulus of elasticity more closely matching that of dentine should be developed, allowing for stress relief within the restorative material. However, the wear properties of such ceramics should approximate those of enamel (Krejci, 1992). Another possible solution might be the use of more elastic composite luting materials. In addition, individual pretreatment methods for each ceramic material should be established to ensure a stress-resistant adhesive interface between ceramics and composite luting agents.

References

Adair P. J. and Grossman D. G. (1984) The castable ceramic crown. *Int. J. Periodont. Rest. Dent.* **2,** 33–45.

Brandestini M., Mörmann W., Lutz F. *et al.* (1985) Computer machined ceramic inlays: *in vitro* marginal adaptation. *J. Dent. Res.* **64,** 208 (abstr. 305).

Bronwasser P. J., Mörmann W. H., Krejci I. *et al.* (1991) Marginal Adaptation von CEREC-Dicor-MGC-Restaurationen unter Verwendung von Dentinadhäsiven. *Schweiz. Monatsschr. Zahnmed.* **101,** 162–169.

Byram J. Q. (1908) *Principles and Practice of Filling Teeth with Porcelain.* New York, NY Consolidated Dental Manufacturing Co.

Davidson C. L., DeGee A. J. and Feilzer A. J. (1984) The competition between the composite–dentin bond and the polymerization stress. *J. Dent. Res.* **63,** 1396–1399.

Diedrich P. and Erpenstein H. (1985) Rasterelektronenmikroskopische Randspaltanalyse von in vivo eingegliederten Stufenkronen und Inlays. *Schweiz. Monatsschr. Zahnmed.* **95,** 575–568.

Dreyer-Jørgensen K. (1958) Prüfergebnisse zahnärztlicher Gussverfahren. *Dtsch. Zahnärztl. Z.* **13,** 461–469.

Geppert W. and Roulet J.-F. (1986) *In vitro* marginal integrity of MOD Dicor inlays luted with adhesive techniques. *J. Dent. Res.* **65,** 731 (abstr. 48).

Grossman D. G. (1985) Cast glass ceramics. *Dent. Clin. North. Am.* **29,** 725–739.

Herder S. M. and Roulet J.-F. (1988) Marginale Adaptation von adhäsiv befestigeten Dicor-Inlays *in vivo. Dtsch. Zahnärztl. Z.* **43,** 904–908.

Joseph V. P. and Cohen J. (1988) Microleakage of porcelain, composite and amalgam restorations. *J. Dent. Res.* **778,** (abstr. 36).

Krejci I. (1992) *Zahnfarbene Restaurationen.* PhD Thesis, Zürich.

Krejci I. and Lutz F. (1990) In-vitro-Testverfahren zur Evaluation dentaler Restaurationen: 3. Korrelation mit In-vivo-Resultaten. *Schweiz. Monatsschr. Zahnmed.* **100,** 1445–1449.

Krejci I., Reich T., Lutz F. *et al.* (1990a) In-vitro-Testverfahren zur Evaluation dentaler Restaurationssysteme. 1. Computer-gesteuerter Kausimulator. *Schweiz. Monatsschr. Zahnmed.* **100,** 953–960.

Krejci I., Albertoni M. and Lutz F. (1990b) In-vitro-Testverfahren zur Evaluation dentaler Restaurationssysteme. 2. Zahnbürsten-/Zahnpastaabrasion und chemische Degradation. *Schweiz. Monatsschr. Zahnmed.* **100,** 1164–1168.

Krejci I. Picco U. and Lutz F. (1990c) Dentinhaftung bei zahnfarbenen adhäsiven MOD-Sofortinlays aus Komposit. *Schweiz. Monatsschr. Zahnmed.* **100,** 1151–1159.

Krejci I., Krejci D. and Lutz F. (1992) Clinical evaluation of a new pressed glass ceramic inlay material over 1.5 years. *Quintessence Int.* **23,** 181–186.

Lutz F., Krejci I. and Barkakow F. (1991) Quality and durability of marginal adaptation in bonded composite restorations. *Dent. Mater.* **7,** 107–113.

Mörmann W. and Brandestini M. (1989) *Die CEREC computer reconstruction.* Berlin, Quintessenz.

Peck A. E. (1902) *Porcelain Inlay: A Treatise on its Theory and Practice in Dentistry.* Minneapolis, Press of A. B. Farnham & Co.

Qualtrough A. J. E., Cramer A., Wilson N. H. F. *et al.* (1991) An *in vitro* evaluation of the marginal integrity of a porcelain inlay system. *Int. J. Prosthodont.* **4,** 517–523.

Reller U., Geiger F. and Lutz F. (1989) Quantitative investigation of different finishing methods in conventional cavity preparations. *Quintessence Int.* **20,** 453–460.

Schibli T. (1991) Verschleissverhalten und marginale Adaptation von keramischen Inlays mit unterschiedlichen Randkonfigurationen. Thesis, University of Zürich.

Shortall A. C., Fayyad M. A. and Williams J. D. (1989) Marginal seal of injection-molded ceramic crowns cemented with three adhesive systems. *J. Prosthet. Dent.* **61,** 24–27.

Sokal R. R. and Rohlf F. J. (1981) *Biometry.* New York, W. H. Freeman & Co.

Tjan A. H. L., Dunn J. R. and Sanderson I. R. (1989) Microleakage patterns of porcelain and castable ceramic laminate veneers. *J. Prosthet. Dent.* **61,** 276–282.

Van Meerbeek B., Inokoshi S., Willems G. *et al.* (1992) Marginal adaptation of four tooth-coloured inlay systems *in vivo. J. Dent.* **20,** 18–26.

International Abstracts

Section Editor: W. R. E. Laird

Assistant Section Editor: Dr A. D. Walmsley

Low power laser biostimulation ved kroniske oro-faciale smerte-tilstande. (Low power laser biostimulation used in the treatment of orofacial pain conditions.)

Thorøe U. and Hansen H. J. (1990) *Tandlægebladet* **94,** 603–612.

The effect of low power laser biostimulation used in the treatment of chronic orofacial pain conditions was studied. The sample consisted of 40 patients with a non-pathological orofacial pain lasting more than 6 months. The investigation was a double-blind placebo-controlled experiment with a modified cross-over design. The laser source was an infrared diode laser with a wavelength of 904 nm (Ora-laser, Oralia, Konstanz, Germany). Two laser probes were used, one active and one inactive. Only the manufacturer of the laser knew which was the active one. The effect of the treatment was recorded as an overall subjective evaluation of possible changes in the level of pain, and also on a visual analogue scale (VAS-pain). The treatment response was correlated with changes in the level of the excretion of 5-hydroxyindolacetic acid (5-HIAA) in the urine.

The results of the overall subjective evaluation of changes in the level of pain indicated that the treatment effect of placebo was superior to that of the laser. No statistically significant differences in the VAS recordings were found between the effect of the laser and placebo. A significant increase ($P = 0.05$) in the excretion of 5-HIAA was demonstrated in the placebo group. *A placebo effect of some magnitude may be expected when a 904 nm IR laser is used in the treatment of patients with orofacial pain conditions.*

(46 references)

Einar Berg

A study of the protrusive condylar paths in edentulous patients.

Shi Sheng-gen *et al.* (1991) *Chin. J. Stomatol.* **26,** 342.

In this study, the inclinations of the condyle paths of edentulous patients were measured by taking protrusive relation records at 2, 4, 6 and 8 mm different protrusive positions, in order to study the patterns of protrusive condylar paths. Thirty-two subjects, 17 males and 15 females, with an average age of 57.8 years were investigated. Left and right inclinations of protrusive condylar path were basically identical at the same protrusive positions, which showed no significant difference ($P > 0.05$). When the protrusive distance was at 2 mm, the inclinations of the condylar paths of some patients were at zero or negative. When the protrusive distance was greater than 2 mm, the inclinations of the condyle paths were positive. The greater the protrusive distance, the greater the value of the inclination of the protrusive condyle path, which showed a significant positive correlation. When the protrusive distances were at 6 mm and 8 mm, the inclinations of the protrusive condyle paths in males were significantly greater than those in females.

The results showed that there was a small range of free forward and backward gliding area of the centric occlusion in full dentures which conformed to the physiological movement of the temporomandibular joints.

(9 references)

Wei Yi

Ceramic inlays (Cerec) cemented with either a dual-cured or a chemically cured composite resin luting agent

A 2-year clinical study

Göran Sjögren, Margareta Molin, Jan van Dijken and Maud Bergman
Department of Dental Materials Science, Prosthodontics, and Cariology, Faculty of Odontology, Umeå University, Umeå, Sweden

Sjögren G, Molin M, van Dijken J, Bergman M Ceramic inlays (Cerec) cemented with either a dual-cured or a chemically cured composite resin luting agent. A 2-year clinical study Acta Odontol Scand 1995,53.325–330. Oslo. ISSN 0001–6357.

On the basis of the criteria of the California Dental Association (CDA), 66 CAD/CAM-manufactured ceramic class-II inlays (Cerec) were compared intraindividually after they had been cemented with either a chemically cured or a dual-cured composite resin luting agent in 27 patients Plaque and gingival conditions, the overall time consumption for producing each inlay, and the frequency of postoperative sensitivity were also evaluated There was no statistically significant difference between the two luting agents with regard to the properties evaluated One inlay was replaced owing to fracture of the restored tooth just before the 24-month re-examination. After 2 years excellent CDA ratings were obtained for color in 92% of the remaining 65 inlays. The corresponding figures for surface and for anatomic form were 100% and 85%, respectively. For margin integrity 85% of the 33 inlays cemented with the dual-cured luting agent and 88% of the 33 inlays cemented with the chemically cured luting agent were rated excellent after 2 years. □ *CAD/CAM; cementation; clinical evaluation; dental materials; dental porcelain*

Göran Sjögren, Department of Dental Materials Science, Faculty of Odontology, Umeå University, S-901 87 Umeå, Sweden

CAD-CAM-manufactured ceramic inlays have been available in dentistry since 1988, when the Cerec CAD-CAM system for dental restorations was introduced onto the market. During the past few years Cerec inlays have been evaluated in longitudinal clinical studies and in in vitro studies (1–4). As in most studies dealing with ceramic inlays, these have usually been cemented with dual-cured composite resin luting agents.

However, there is some doubt about the setting of dual-cured resin luting agents under restorations, since the setting of dual- and light-cured luting agents depends to a great extent on exposure time and the intensity of the light source (5–8). Ceramic attenuates light depending on its thickness and shade (5–7), and the chemically activated components in dual-cured luting agents do not provide complete hardening of the luting agent in those parts of a tooth not reached by the curing light. For example, Breeding et al. (7) have shown that the chemical curing in dual-cured composite resin luting agents can be incapable of compensating for inadequate light exposure and possesses limitations similar to light-activated luting agents. Moreover, in a study by Rueggeberg & Caughman (8) no evidence was found for a substantial chemically induced polymerization of dual-cure resins after light exposure is completed. Thus, the polymerization can be incomplete under thick ceramic restorations, and maximal support of the luted ceramic restorations is not obtained, since the ultimate hardness of dual-cured luting agents depends on the amount of exposure to the curing light.

The aim of the present study therefore was to compare Cerec ceramic inlays luted either with a two-component chemically cured or with a dual-cured composite resin luting agent in an intraindividual study.

Materials and methods

Sixty-six Cerec ceramic class-II inlays (Vita Cerec Mark II, Vita Zahnfabrik, Bad Säckingen, Germany) were manufactured, using the CAD/CAM technique (Cerec System, software C.O.S. 2.0, Siemens AG, Bensheim, Germany) in accordance with the manufacturer's instructions (9) by three dentists. The inlays were placed on molars or premolars in 27 patients who regularly visited Public Dental Health Service Clinics or Umeå University Dental School. The subjects, 17 female and 10 male patients, ranged in age from 15 to 65 years (mean, 37 years).

At the initial examination routine anamnestic records and any symptoms from the temporomandibular joint (TMJ), masticatory muscles, and oral mucosa were monitored.

Twenty-two of the patients received two inlays each, four patients four inlays each, and one patient six inlays. Thirteen molars, 4 of them second molars, and 53 premolars were restored. Fifteen inlays were 3-surface restorations on premolars and 2 were 3-surface restorations on molars, 38 inlays were 2-surface restorations on premolars, and 11 were 2-surface restorations on molars. The indication for the treatment was primary caries for 20 inlays and replacement of amalgam or composite fillings for the rest. In the latter cases the reasons for replacing the amalgam or the composite fillings were secondary caries or fear of side effects from the amalgam and, in one case, oral lichen planus.

The preparation design of the cavities was in accordance with the manufacturer's instructions (9). Dentinal areas near the pulp were protected with a calcium hydroxide base (Dycal, L.D. Caulk Co., Milford, Del., USA), and a glass-ionomer cement (Baseline, De Trey Dentsply, Konstanz, Germany) was placed as a base in very deep parts of the cavities and for blocking undercuts. To make it possible to analyze a potential influence of the preparation design in case of any fracture of an inlay, an impression of each prepared cavity was taken with an A-silicon (President, Coltène, Altstätten, Switzerland) or an alginate hydrocolloid (Algi-X, Svedia-Dental Industri AB, Enköping, Sweden), and stone die models were made (Kerr Vel-Mix Stone ISO Type IV, Kerr Europe AG, Basel, Switzerland). Fifty-four of the inlays were made directly and 12 indirectly on die stone models. The ceramic blocks used were Vita Cerec Mark II (Vita Zahnfabrik).

Before the inlays were luted, the enamel was etched with a 36% phosphoric acid gel, and the teeth were subsequently rinsed with water and dried with compressed air. A dentin bonding agent (Gluma, Bayer, Leverkusen, Germany) was placed on the dentin, followed by spraying with air. Enamel bonding agents used were those recommended by the manufacturers of the resins (Coltene Duo Bond Kit, Coltène, batch 9205-510, and Cavex Clearfil F2, Cavex Holland BV, RW Haarlem, Holland, batch 911001, respectively).

On a randomized basis half the number of the inlays in each patient were cemented with a two-component, dual-cured hybrid composite resin luting agent (Cerec Duo Cement, batch 9110-983) and the rest with a chemically cured hybrid composite resin luting agent that was primarily intended as a filling material for anterior teeth (Cavex Clearfil F2, batch 910415). Previously, the inlays had been etched with 4.9% HF acid for 1 min (Vita Cerec-Etch, Vita-Zahnfabrik) and silane-treated for 1 min (Ultradent Silane, Ultradent Products Inc., Utah, USA) in accordance with the manufacturers' instructions. To prevent excess of the luting agent at the proximal margins, plastic or metal strips and wooden wedges were used. For each restoration cemented with the Cerec Duo Cement the luting agent was light-cured by means of a dental photocuring lamp (ICI Model 4000, Imperial Chemical Industries PLC, Cheshire, England, or Norlite, Dencon GmbH, Bremen, Germany) for 60 sec each from the occlusal, buccal, and lingual/palatinal surfaces.

After being luted the inlays were contoured and adjusted in occlusion and articulation. Excess luting agent was removed with fine diamonds (Cerec-Set, 40 μm), and the restorations were polished with superfine diamonds (Cerec-Set, 15 μm), rubber polishers (Shofu Ceramisté, Shofu Inc., Kyoto, Japan), SofLex polishing discs (3 M Dental Product Division, St Paul, Minn., USA), and diamond paste (Ultradent Diamond polish, Ultradent Products Inc., Utah, USA).

The position of the cervical proximal inlay margins and the total time needed for manufacturing each inlay, including all the steps from preparation to luted and polished inlay, were recorded.

Evaluation

Two weeks after luting (*base line*) and after 12 and 24 months the patients were recalled, and the inlays were examined in accordance with the California Dental Association's (CDA) quality evaluation system (10) after calibration of four evaluators, working in pairs but independent of each other. The surface and color, anatomic form, and marginal integrity were evaluated. Whenever disagreements occurred, the two evaluators resolved them by joint examination. At each recall the patients were also interviewed for postoperative sensitivity, in accordance with the system used by Borgmeijer et al. (11).

In addition, at the 24-month re-examination plaque and gingival conditions were registered by one of the examiners. The plaque and bleeding indices used were in accordance with Lenox & Kopczyx (12). Surfaces with Cerec inlays were compared with surfaces without Cerec restorations on adjacent teeth. Molars were always compared with molars and premolars with premolars. When the adjacent tooth was lost or was unsuitable for other reasons, such as being provided with a temporary restoration, the control tooth had to be chosen in other quadrants. Corresponding surfaces were always compared with each other; for example, a mesial Cerec inlay surface was compared with the mesial surface of the control tooth.

Statistical analysis

The values obtained for the CDA scores both for the occurrence of shallow marginal ditching and for the plaque and gingival conditions for each type of luting agent were analyzed statistically, using the test of difference of proportions.

Results

The initial clinical examination showed that one patient had clicking sensations from the TMJ and three patients had tenderness on palpation from the masticatory muscles. Ten patients had tooth wear rated grade II–

Table 1. Percentages and numbers of inlays that did *not* receive an excellent CDA rating* for margin integrity, anatomic form, color, and surface (n = 33 for each group, with the exception of the dual-cured luted inlays in the groups anatomic form, color, and surface at the 24-month re-examination, n = 32, since one inlay had been replaced by a crown)

	Dual-cured						Chemically cured					
	Base line		12 months		24 months		Base line		12 months		24 months	
	%	n	%	n	%	n	%	n	%	n	%	n
Margin integrity												
SDIS			3	1	9	3			3	1	6	2
SCR	3	1	3	1	3	1					3	1
VFR											3	1
VTF					3	1						
Anatomic form												
SCO	6	2	6	2	3	1	3	1				
SPX	3	1					3	1				
SUCO							6	2	9	3	6	2
SOCO	6	2	6	2	6	2	6	2	9	3	6	2
SMR			3	1	3	1			3	1	3	1
SOH			3	1	3	1						
Color												
SMM	9	3	6	2	9	3	9	3	6	2	6	2
Surface												
SRO									3	1		

* SDIS = discoloration on margin between the restoration and the tooth structure; SCR = visible evidence of ditching along the margin not extending to the dentinoenamel junction; VFR = fracture of the restoration; VTF = tooth structure fractured; SCO = contact slightly open (may be self-correcting); SPX = interproximal cervical area slightly undercontoured, SUCO = restoration is slightly undercontoured; SOCO = restoration is slightly overcontoured; SMR = marginal ridges slightly undercontoured; SOH = occlusal height reduced locally (not in toto), SMM = slight mismatch between restoration and tooth structure within normal range of tooth color, shade, and/or translucency; SRO = surface of restoration is slightly rough or pitted, can be polished.

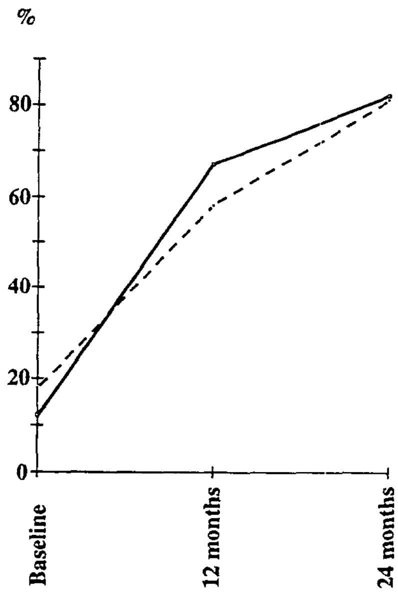

Fig. 1. Percentage of inlays with ditching at the occlusal margins; n = 33 at each examination with the exception of the inlays cemented with the dual-cured luting agent at the 24-month re-examination, at which n = 32 owing to fracture of a lingual cusp. Broken line = dual-cured; continuous line = chemically cured.

III in accordance with the rating system suggested by Eccles (13). No changes were observed during the follow-up period.

No statistically significant difference was observed between the two luting agents used with regard to the properties evaluated. Frequencies of the CDA scores for the evaluated factors are given in Table 1.

All inlays were rated satisfactory at each examination by means of the CDA rating system, with the exception of two inlays at the 24-month re-examination. One of those inlays was rated VFR (fractured restoration) and the other was rated VTF (tooth structure fractured). The latter inlay had been replaced with a ceramic crown just before the 24-month re-examination owing to fracture of the restored tooth.

With regard to margin integrity, 85% of the inlays cemented with the dual-cured luting agent and 88% of the inlays luted with the chemically cured luting agent were rated excellent at the 24-month re-examination (Table 1). However, when the margins were examined with an explorer, the explorer did not stick but registered differences in height because of shallow ditches around the occlusal margins of the inlays (Fig. 1). As can be seen in Fig. 1, the number of inlays with clinically detectable occlusal margins increased during the follow-up period, but these inlays still fulfilled the requirements to be rated 'excellent' with regard to margin integrity according to the CDA rating system. At the proximal and cervical margins no wear of the luting agent could be detected when examined with an explorer. No clinical evidence of marginal caries was seen in any of the inlays after 24 months.

The interexaminer agreement for the CDA quality rating exceeded 85% at each examination.

Six patients showed postoperative sensitivity related to one of their inlays (9% of the inlays). Two patients reported sensitivity to heat and cold lasting 1 or 2 weeks, and one reported such sensitivity lasting for a couple of days. The three teeth concerned had been exposed to excessive polishing at the cervical margins during removal of excess luting composite. One patient reported sensitivity on loading lasting for a couple of days, one patient reported sensitivity to heat and cold that remained at the 12-month re-examination, and another patient reported occasional sensitivity both to cold and on loading, still remaining at the 24-month re-examination. Three of the teeth that showed post-operative symptoms had inlays cemented with the dual-cured luting agent and three of them had been cemented with the chemically cured luting agent.

Table 2. Margin index score* of Cerec proximal surfaces

Dual-cured					Chemically cured				
Surface	Score 0	Score 1	Score 2	Score 3	Surface	Score 0	Score 1	Score 2	Score 3
Base line					Base line				
Mesial (n = 16)		1	6	9	Mesial (n = 15)			5	10
Distal (n = 25)		3	9	13	Distal (n = 27)		2	9	16
12 months					12 months				
Mesial (n = 16)	1	1	5	9	Mesial (n = 15)			3	12
Distal (n = 25)		3	8	14	Distal (n = 27)		2	9	16
24 months					24 months				
Mesial (n = 15)†		1	4	10	Mesial (n = 15)			3	12
Distal (n = 24)†		1	9	14	Distal (n = 27)		2	10	15

* Score 0 = restoration margin >2 mm above the gingival margin, score 1 = <2 mm above the margin; score 2 = at the gingival margin; score 3 = below the gingival margin.
† One inlay had been replaced with a crown owing to fracture of the lingual cusp

Even though some of the patients in the present study had parafunctional habits (tooth grinding, tooth clenching) and had first and second molars treated with Cerec inlays, none of the 66 inlays fractured during the follow-up period, with the exception of a minor chip fracture at the margin of one of the inlays. This was easily adjusted, and the inlay is still functioning. In addition, the lingual cusp of one of the restored premolars was fractured just before the 24-month re-examination, and the inlay had to be replaced with a ceramic crown.

Most of the Cerec inlays had margins placed subgingivally or at the level of the gingival margin. No systematic changes of the level of this margin were observed during the follow-up period (Table 2). At the 24-month re-examination proximal plaque and bleeding on probing were not seen more often on Cerec inlay surfaces than on the corresponding surfaces of the control teeth without Cerec inlays, and no statistically significant difference was observed between the two luting agents used (Table 3).

The average total time taken to make the Cerec class-II inlays was 1 h and 50 min (range, 1 h to 2 h and 30 min), and there was no systematic difference in the time taken between restorations produced directly and those produced indirectly. All the inlays placed on second molars had been produced indirectly, since there was limited space for the miniature video camera when the rubber-dam was seated. They also needed the longest time, not because they were manufactured indirectly but because they were replacements for fairly large amalgam fillings.

Discussion

The luting technique for ceramic inlays is important, and the properties of the luting agent are crucial for the

Table 3. Relative number and percentage of proximal surfaces with plaque and with bleeding on probing at the 2-year examination

	Surfaces with plaque				Surfaces with bleeding on probing			
	Dual-cured Cerec surfaces (n = 39)		Chemically cured Cerec surfaces (n = 42)		Dual-cured Cerec surfaces (n = 39)		Chemically cured Cerec surfaces (n = 42)	
Surface	Relative no.	%	Relative no.	%	Relative no.	%	Relative no	%
Mesial	7/15	46.7	10/15	66 7	1/15	6.7	2/15	13.3
Distal	17/24	70.8	16/27	59.2	7/24	31.8	7/27	25.9
Total	24/39	61.5	26/42	61.9	8/39	20.5	9/42	21.4
	Control surfaces (n = 39)		Control surfaces (n = 42)		Control surfaces (n = 39)		Control surfaces (n = 42)	
Surface	Relative no.	%	Relative no.	%	Relative no.	%	Relative no.	%
Mesial	9/15	60.0	10/15	66 6	4/15	26.7	2/15	13.3
Distal	16/24	66.7	15/27	55 5	8/24	33.3	8/27	29 6
Total	25/39	64.1	25/42	59 5	12/39	30.8	10/42	23.8

Fig. 2. Radiograph of 25 DO, 35 DO Cerec restorations cemented with Cerec Duo luting agent and 36 MO Cerec restoration cemented with Cavex Clearfil F2 luting agent and with a class-V amalgam filling.

longevity of the restorations. According to the manufacturers' information the luting agents in the present study are both classified as hybrid composite resins with medium to heavy viscosity.

However, at the moment when a restoration is seated, the viscosity of the luting agent also depends on the curing system. Both dual-cured and chemically cured composite resin luting agents begin to set when the components are mixed together; that is, their viscosity increases with time but at different rates depending on the curing system, among other things. The increasing viscosity may make it difficult to place the inlays, especially with chemically cured resins. Judging from the findings in the present study the working time seems to have been sufficient for a clinically acceptable seating of the restorations even for the chemically cured luting agent used.

In the present study shallow ditching around the inlays' margins due to wear of the luting agent was only observed on the occlusal surfaces. Van Dijken & Hörstedt (14) have also reported, in a study of Mirage inlays, that ditching around the margins of the inlays was observed more often in relation to occlusal margins than to proximal margins.

With regard to the CDA rating for the margin integrity (Table 1) and the occurrence of shallow ditches around the inlay margins (Fig. 1), there was no statistically significant difference between the two types of luting agent used in the present study. As can be seen in Fig. 1, the increase in the number of inlays with clinically detectable occlusal margins was most pronounced between base line and the 12-month re-examination and then tended to decrease. This is in accordance with the findings in a 3-year clinical study of 121 Cerec restorations by Isenberg et al. (4). They reported that clinically detectable margins increased rapidly during the 1st year but then leveled off.

With regard to surface smoothness it was shown in a previous study of 205 Cerec inlays (2) that only 26% of the inlays were rated excellent for the CDA criterion surface. The corresponding figure in a study of 205 Optec inlays (15) was 14%. The rest of the inlays in both studies were rated SRO (surface of restoration is slightly rough or pitted, can be refinished). However, at the 24-month re-examination 100% of the inlays in the present study were rated excellent for surface (Table 1). This means that it appears to be possible to polish Cerec inlays clinically to smooth, well-finished surfaces. In this context it should be observed that excessive polishing and use of abrasive pastes may also cause both postoperative sensitivity and undesirable wear of the luting agent, and the possibility cannot be excluded that the shallow ditches around the occlusal margins registered at base line (Fig. 1) have been caused by the grinding and polishing procedures.

The 24-month examination of plaque and bleeding on probing showed good results (Table 3). There was no more plaque or bleeding on probing in connection with the Cerec restorations than with the control surfaces at the 24-month examination. Therefore, it seems reasonable to assume that the materials used for the restorations do not have an injurious effect on the gingival conditions. However, the validity of this assumption can only be clarified after long-term observation, and the registrations carried out (Table 3) are intended to be followed up in a long-term study.

A clinically important property of luting agents is their radiopacity, especially since the radiographic density of many ceramics is less than that of dentin (16). One disadvantage of the chemically cured resin luting agent used in the present study is therefore its low radiopacity (Fig. 2).

Six of the 66 teeth with Cerec inlays in the present study showed slight postoperative sensitivity, but none of the patients complained of the type of sharp, clearly localized pain on loading of the inlays which has been reported in connection with posterior composite or ceramic inlays (17, 18). Besides the fact that the inlays in the present study were very carefully adjusted in occlusion and articulation, the dentin adhesive used (Gluma) may have inhibited this particular symptom, in accordance with the theory of short-circuiting the surfaces, which prevents the influence of generated electricity on the surfaces of the ceramics (19).

Conclusion

The Cerec restorations showed an almost ideal clinical performance after 2 years, and there was no significant difference between the two types of luting agent used with regard to the properties evaluated. As judged by the findings in the present intraindividual study, chemically cured luting agents may therefore serve as an alternative luting agent for ceramic inlays with mechanical properties similar to those of the ceramic used in the present study. However, further studies are necessary to predict the long-term performance of the restorative systems concerned.

Acknowledgements.—This work was supported by the Swedish Medical Research Council (project 09447) and by the County Council of Västerbotten, Sweden.

References

1. Mörmann W, Krejci I. Computer-designed inlays after 5 years in situ; clinical performance and scanning electron microscopic evaluation. Quintessence Int 1992;23:109–15
2. Sjögren G, Bergman M, Molin M, Bessing C. A clinical examination of ceramic (Cerec®) inlays Acta Odontol Scand 1992; 50:171–8.
3. Rose D, Platzer U, Roth KK. Untersuchungen zur Kompositfuge bei computererstellten Keramikinlays. Dtsch Zahnaerztl Z 1990; 45.677–9.
4. Isenberg BP, Essig ME, Leinfelder KF. Three-year clinical evaluation of CAD/CAM restorations J Esthet Dent 1992;4:173–6.
5. Blackman R, Barghi N, Duke E Influence of ceramic thickness on the polymerization of light-cured resin cement. J Prosthet Dent 1990;63:295–300.
6. Brodbelt RHW, O'Brien WJ, Fan PL. Translucency of dental porcelain. J Dent Res 1980,59:70–5.
7. Breeding LC, Dixon DI, Caughman WF. The curing potential of light-activated composite resin luting agents. J Prosthet Dent 1991; 65:512–8.
8. Rueggeberg FA, Caughman WF. The influence of light exposure on polymerization of dual-cure resin cements Oper Dent 1993,18· 48–55.
9. Mörmann W, Brandetini M Die Cerec Computer Reconstruction. Inlays, Onlays und Veneers. Berlin: Quintessenz Verlags-GmbH, 1989.
10. Quality evaluation for dental care. Guidelines for the assessment of clinical quality and professional performance. Los Angeles. California Dental Association, 1977.
11. Borgmeijer PJ, Kreulen CM, van Amerongen WE, Akerboom HBM, Gruythuysen RMJ. The prevalence of postoperative sensitivity in teeth restored with class II composite resin restorations. J Dent Child 1991;58:378–83.
12. Lenox JA, Kopczyk RA. A clinical system for scoring a patient's oral hygiene performance. J Am Dent Assoc 1973;86:849–52.
13. Eccles JD. Dental erosion of nonindustrial origin. A clinical survey and classification. J Prosthet Dent 1979;42:649–53
14. van Dijken JWV, Hörstedt P. Marginal breakdown of fired ceramic inlays cemented with glass polyalkenoate (ionomer) cement or resin composite. J Dent 1994;22:265–72
15. Molin M, Karlsson S. A clinical evaluation of the Optec inlay system. Acta Odontol Scand 1992;50.227–33.
16. el-Mowafy OM, Brown JW, McComb D. Radiopacity of direct ceramic inlay restoratives. J Dent 1991;19:366–8.
17. Haller B, Hofmann N Postrestorative sensitivity; Mechanisms and prevention. International Symposium on Computer Restorations· State of the art of the Cerec-method. Proceedings. Berlin· Quintessence Publishing Co Inc, 1991.127–39.
18. Hickel R. Zur Problematik hypersensibler Zähne nach Eingliederung von Adhäsivinlays. Dtsch Zahnaerztl Z 1990;45:740–2.
19. Sjogren G, Bergman M, Johansson K. Piezoelectricity in dental materials, a conceivable cause of postrestorative sensitivity. Acta Odontol Scand 1992;50:313–19.

Received for publication 2 January 1995
Accepted 27 January 1995