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ORIGINAL ARTICLES

Pulpal Response to a New Light-cured Composite Placed in Etched Glass-Ionomer Lined Cavities

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C HARNIRATTISAI • M OTSUKI

Summary

This study evaluated the pulp biocompatability of a new light-cured composite resin which was placed in etched glass-ionomer-lined cavities of monkey teeth. The pulpal response to this material was less than that to zinc-oxide eugenol cement in each observation period. Therefore this material seems to meet acceptable biocompatability standards in nonhuman primates.

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INTRODUCTION

Visible-light-cured composites are essential for the aesthetic restoration of anterior teeth, and color matching of the resins to the remaining tooth structure is of prime concern for the general practitioner. A new light-cured composite, Graft LC (G-C Industrial Corp, Scottsdale, AZ 85260) matches the Vita VMK 68 (Vita Zahnfabrik H Rauter GmbH & Co, Säckingen, Germany) shades to facilitate simpler color matching. Graft LC contains glass filler particles treated with graft binders to reinforce the matrix-particle interface.

Hosoda and others (1988) classified this resin as a heavily filled composite, containing two kinds of glass filler particles in which Si, Ba, and Al, and Si were detected respectively. The resin showed a relatively small surface roughness (R max = 0.65 μm) after polishing, in spite of its relatively large filler particle size distribution. According to a degradation test in alkaline solution, the filler particles were retained in the subsurface damaged layers, indicating improved interfacial bonding (Hosoda & others, 1988).

Hirabayashi and others (1990) reported that Graft LC, unlike the other composite resins studied, showed no interfacial degradation and the smallest decrease in bending strength after 50 000 thermal stress cycles between 4 and 60 °C in water. They concluded that the new graft binders greatly improved the durability of

EDITORIAL

Electronic Journals: The Demise of the Printed Journal?

Technology marches on. Changes are occurring faster than most of us can keep up with. In recent years the number of journals being published has increased at an alarming rate, and so have the costs. Universities and other institutional libraries can no longer afford to subscribe to all journals. A result is that many libraries are cutting or eliminating serial publication subscriptions. The proposed mechanism for distribution of scientific publications is the creation of an electronic "Scholarly Publication System." If this replaces the present serial publications, what will happen to the journals now in publication?

There is no doubt that we will see many changes in the way that scientific publications are printed and distributed. If institutions cannot afford the cost of printed matter, it seems reasonable that they will substitute it with electronic media. Just think of the potential. If you wanted to read current information, it could be done as fast as you can boot your computer, whereas with the printed matter, most material is one to three years old before it gets printed. Electronic journalism would end that. Material placed on a computer network of scholarly publications would be available as soon as it is copied onto the computer. For the very first time, we could all have real-time information on current products data, information on new techniques, and other matters relating to our own personal interests. Sounds great, doesn't it? But is it?

If universities are the promoters of such electronic publication media, you can rest assured that all faculty will need to publish their works on this new medium and not in the traditional journals. Journals as we know them today will be very limited by their lack of access to material to publish. Many, if not most, will fold as there will not be sufficient numbers of manuscripts for the electronic and printed media together.

Will we still have a few private, printed journals around after this new age dawns? In all probability we will continue to have a few journals, but they will be relegated to printing opinions and other solicited manuscripts as well as information from and about the journals' sponsoring agencies. The advent of electronic publishing of refereed materials is on the way and with it we will see a rapid decrease in the number of journals on the market.

Is this a good thing? From the start it will enhance the lives of many in academia. Over a period of time the various professions will all become computer-wise and will have a much wider variety of current material at their fingertips. What a giant step forward. Journals printed on paper are in their last decade, but time needs to move on. So be it!

DAVID J BALES
Editor

this composite resin compared with conventional silane coupling agents.

For clinical usage, the manufacturer recommends using the sandwich technique (McLean, Prosser & Wilson, 1985), meaning all dentinal cavity walls and the floor should be lined with a glass-ionomer lining cement prior to acid-etching and placement of the composite to avoid possible pulp irritation from the composite resin restoration.

In this study, pulpal response to the new material (used according to the manufacturer's instructions) was investigated according to the Commission specification guidelines (Commission on Dental Materials, Instruments, Equipment, and Therapeutics, 1980).

MATERIALS AND METHODS

Seventy-five class 5 cavities were prepared in the teeth of three monkeys under systemic narcosis by intravenous injection of Ketalar (Sankyo Co, Tokyo, Japan), 20 mg/kg, using inverted cone-shaped diamond stones (#1421ss, Shofu, Inc, Kyoto, Japan) at high speed under water-spray coolant. An effort was made to prepare the cavities as deep as possible without pulp exposure.

The restorative materials employed are listed in Table 1. For the composite resin restoration group, concave bevels were added at the enamel margins with round-shaped fine diamond stones (#D4012f, G-C Industrial Corp). The cavities were washed and air-dried, and then all dentinal walls were covered with the glass-ionomer lining cement (mixed according to the manufacturer's instructions) without dentin pretreatment. After the lining cement had set, the cavity was etched with 40% phosphoric acid gel etchant for 60 seconds, washed, air-dried, and covered with a thin coating of bonding agent. The light-cured composite was then immediately placed in the cavities as a bulk, and cured for 60 seconds (Fig 1).

The negative control material was a zinc oxide-eugenol cement, Eugadain (Showa Yakuhin Kako Co, Ltd, Tokyo, Japan), and the positive control material was a silicate cement, Syntrex F (L D Caulk Co, a Division of Dentsply International, Milford, DE 19963). These were placed

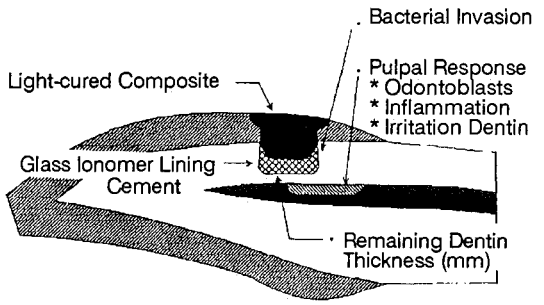

FIG 1. *Schematic illustration of the new resin placed in an etched glass-ionomer lined cavity and parameters of histopathological evaluation*

Table 1. Materials Employed in this Study

Materials	Trade Name	Composition	Batch #	Manufacturer
Test materials	Graft LC	semi-hybrid composite	280991	G-C Industrial Corp Scottsdale, AZ 85260
	G-C Bonding Agent	low viscosity unfilled resin	B:300691 C:070692	
	G-C Etching Liquid	phosphoric acid	220691	
	G-C Lining Cement	glass-ionomer cement	P:180791 L:0017Q	
Control materials	Eugedain	zinc oxide-eugenol cement	P:2020T L:0017Q	Showa Yakuhin Kako Co, Ltd, Tokyo, Japan
	Syntrex F	silicate cement	P:4207 L:73242	The L D Caulk Co, a Division of Dentsply International Milford, DE 19963

Table 2. Summary of Results

Material	Time Intervals (Days)	# of Specimens	Remaining Dentin Thickness (mm) Average (Min-Max)	Disarrangement & Reduction of Odontoblasts				Inflammatory Reaction				Irritation Dentin Formation			
				none	slight	mod	sev	none	slight	mod	sev	none	slight	mod	sev
Graft LC	3	10	0.57 (0.12-1.20)	1	5	4	0	6	4	0	0	10	0	0	0
	30	10	0.82 (0.30-1.25)	4	5	1	0	6	4	0	0	6	4	0	0
	90	10	0.91 (0.16-1.37)	7	1	2	0	8	2	0	0	6	4	0	0
Eugedain	3	10	0.87 (0.22-2.05)	0	6	3	1	5	3	2	0	10	0	0	0
	30	10	0.50 (0.02-1.40)	2	7	0	1	2	3	3	2	3	6	1	0
	90	10	0.48 (0.04-0.94)	4	4	2	0	3	5	2	0	1	4	1	4
Syntrex F	3	5	0.55 (0.14-0.78)	0	2	3	0	2	3	0	0	5	0	0	0
	30	5	0.63 (0.04-1.07)	0	3	0	2**	0	2	0	3**	3*	1*	1	0
	90	5	0.53 (0.14-0.77)	0	4****	1*	0	0	1*	1*	3***	1*	2**	1*	1*

Number of the "*" mark indicates the section which showed bacterial invasion

directly into the cavities without lining or acid pretreatment. The zinc oxide-eugenol cement base was covered with another zinc oxide-eugenol cement, IRM (L D Caulk), to reinforce the restoration.

After 3, 30, and 90 days, the monkeys were sacrificed by intravenous injection of Ravonol (Tanabe Pharmaceutical Co, Osaka, Japan), 250 mg/kg, and histopathological serial sections at 5 μm thick were prepared. These were stained with hematoxylin and eosin for routine histological evaluation and with Taylor's modification of Gram's staining technique for microorganisms (Taylor, 1966). The sections showing minimum remaining dentin thickness, as measured parallel to the dentinal tubules, were selected for assessment. The intensities of the histological response were arbitrarily classified into four grades: none, slight, moderate, and severe (Mjör & Tronstad, 1972). The presence of bacteria along the cavity walls and floor was also evaluated.

For statistical analysis, disarrangement and reduction of odontoblasts, inflammatory reaction, and irritation dentin formation were considered. Chi-square analysis was used to determine if a significant difference existed between three time intervals (3, 30, and 90 days) of the test group, and between the test group and the negative and positive controls.

RESULTS

Findings on the histological sections and mean values and ranges of the remaining dentin thickness are summarized in Table 2 and Figure 2. The cases displaying evidence of bacterial penetration are indicated by an asterisk in Table 2 and underlining in Figure 2.

There were no statistically significant differences among the remaining dentin thicknesses of the nine groups tested using the Mann-Whitney U test (Siegel, 1956).

Figures 3-7 show representative histological pictures of this study.

Disarrangement and Reduction of Odontoblasts

The disarrangement and reduction of odontoblasts at three days, a sign of initial damage caused by restorative procedures and materials, was comparable in all three groups at the three-day interval, and decreased with time except for the silicate cement group. Among the three time intervals, a statistically significant difference was found between the three- and 90-day intervals ($P < 0.01$). The comparison of the test and control groups showed a significant difference between the silicate cement group only at 90 days ($P < 0.05$).

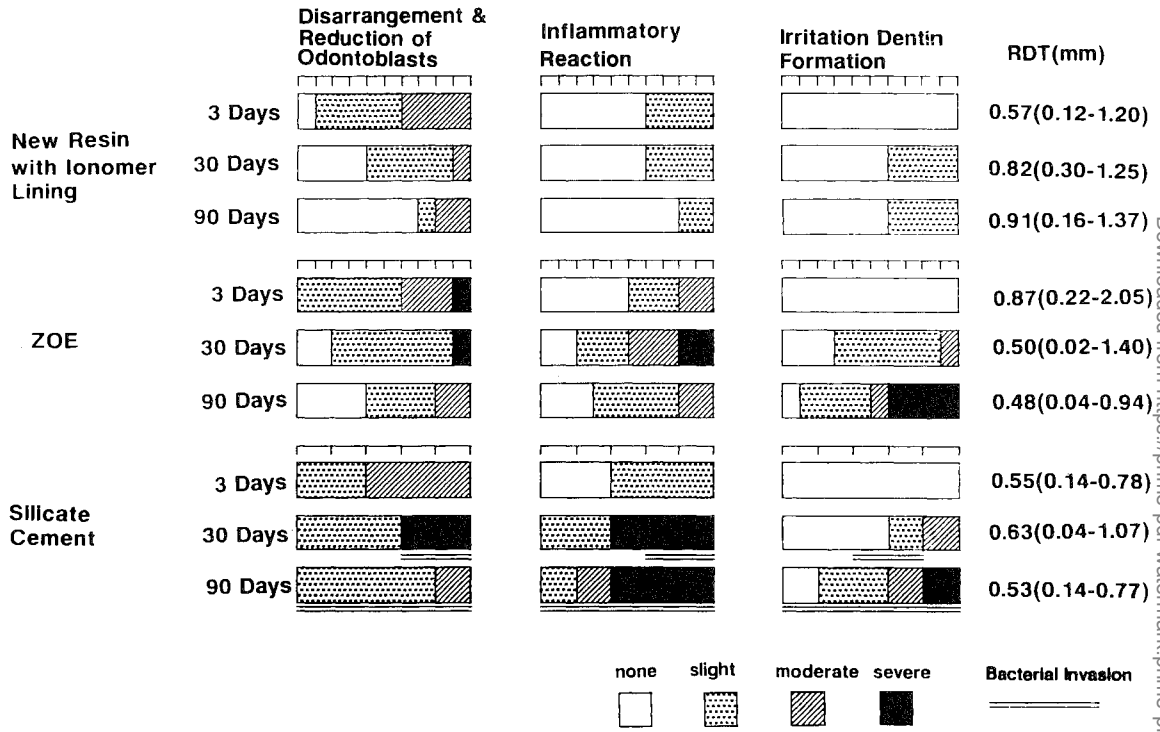

FIG 2. *Pulpal response to the three materials*

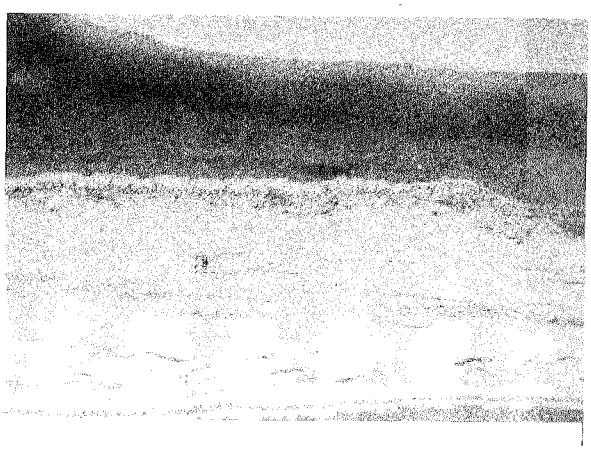

FIG 3. *The new resin after three days; remaining dentin thickness 0.51 mm (H & E stain) (magnification X42)*

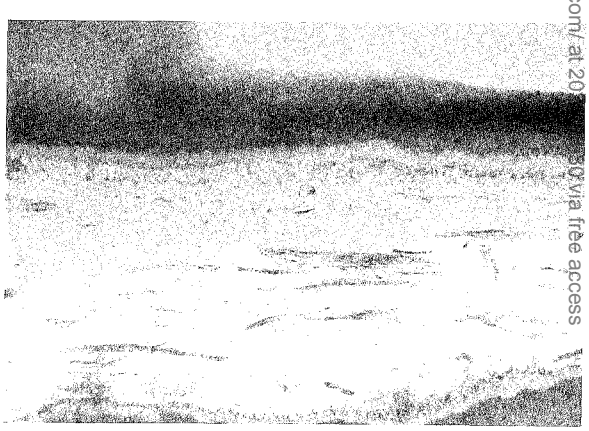

FIG 4. *The new resin after 30 days; remaining dentin thickness 0.30 mm (H & E stain) (magnification X42). Moderate disarrangement and reduction of odontoblasts, slight inflammatory cell infiltration, and slight irritation dentin formation*

FIG 5. *The new resin after 90 days; remaining dentin thickness 0.45 mm (H & E stain) (magnification X42). Slight irritation dentin formation*

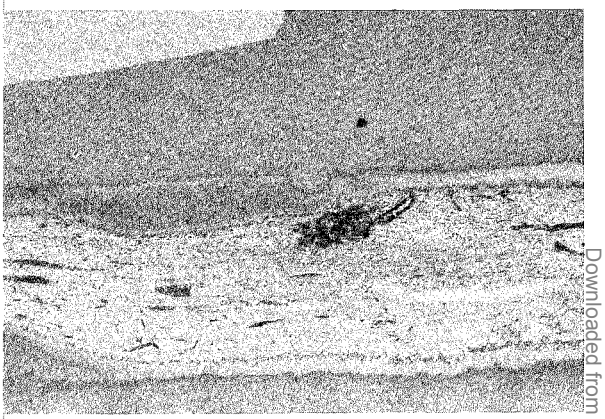

FIG 6. *Silicate cement after 90 days; remaining dentin thickness 0.41 mm (H & E stain) (magnification X42). Severe disarrangement and reduction of odontoblasts, severe inflammatory cell infiltration, and moderate irritation dentin formation*

FIG 7. *Zinc oxide-eugenol cement after 90 days; remaining dentin thickness 0.58 mm (H & E stain) (magnification X42). Moderate disarrangement and reduction of odontoblasts, moderate inflammatory cell infiltration, and moderate irritation dentin formation*

Inflammatory Reactions

The zinc oxide-eugenol cement showed slight to moderate responses at each interval, and two cases of a severe reaction at 30 days. Only at 90 days was a significant difference found between the zinc oxide-eugenol group and the test group ($P < 0.05$).

The silicate cement showed a minimal response at three days, but abruptly increased with time. At 30 and 90 days two-thirds of the specimens showed a severe reaction, and at these two time intervals a significant difference was found between the silicate cement group and the test groups ($P < 0.01$).

The Graft LC composite resin with lining showed the least response of all. The inflammatory reactions were none to slight at all time intervals, even less than those of the zinc oxide-eugenol cement, which showed slight to moderate responses at each interval, with no significant difference.

Irritation Dentin Formation

Irritation dentin formation was found as early as 30 days in all cases. At 90 days the zinc oxide-eugenol cement group showed the greatest amount of irritation dentin formation and the Graft LC group showed the least, which was determined as being statistically different ($P < 0.05$). Among the three time intervals of the test groups, statistically significant differences were found ($P < 0.05$).

Bacterial Penetration

Bacterial penetration could not be detected in any cases of the zinc oxide-eugenol cement and Graft LC composite groups, partly because the presence of cement remnants disturbed detection. A thick layer of bacteria, however, was found along the cavity walls and floor of the

silicate cement group, together with cement remnants. The presence of bacteria was noted to increase markedly with time. It should be pointed out that there were many inflammatory reactions, two even severe, but without bacterial invasion in the zinc oxide-eugenol category, which disputes the Brännström concept (Brännström & Nyborg, 1973).

DISCUSSION

Composite resin restorations placed in unlined cavities have been reported to cause pulpal damage by many investigators. Their irritation has been attributed to toxic chemical substances released from the resin (Langeland & others, 1966; Stanley, Swerdlow & Buonocore, 1967; Rao, 1971), bacteria introduced by microleakage or contamination before placement (Brännström & Nyborg, 1973) and separation of the resin restoration at the cavity floor (Inokoshi, Iwaku & Fusayama, 1982; Fujitani, 1986). No matter what irritates the pulp, permeability of the floor dentin plays an important role for the onset of pulpal irritation, and sealing of the tubular apertures of the cavity preparation either by cement linings or dentin adhesives prevents extrinsic irritants from penetrating into the dentinal tubules, thus protecting the dental pulp.

With the Graft LC composite, the manufacturer's recommendation to line the dentinal walls and floor with the ionomer cement to avoid possible pulp irritation proved true.

In this study, the pulpal response to the composite resin placed in etched glass-ionomer lined cavities was less than that to the zinc oxide-eugenol cement at all time intervals and in all features of histological evaluations, namely odontoblastic disarrangement and reduction, inflammation and irritation dentin formation. These findings proved that the glass-ionomer lining cement covering all dentinal walls and floor protected the pulp from the acid-etching technique and the composite resin.

Disarrangement and reduction of the odontoblasts at three days indicates initial damage of the pulp from restorative procedures (Seltzer & Bender, 1984). It was reported that direct etching of dentinal walls caused a greater reduction of odontoblasts than occurred without etching (Fujitani, 1986). Minimal change of the odontoblastic layer in the Graft LC group at three days suggests that the glass-ionomer lining cement covering all dentinal walls and floor protects the pulp sufficiently from acid pretreatment prior to placement of the composite.

Inflammatory reactions to the silicate cement restoration were the most severe of all groups. The reaction increased as bacterial invasion increased with time. Bacterial invasion is a sign of separation of the cement from the cavity walls, so that microleakage and resulting bacterial invasion could be the main cause of the severe reaction.

The zinc oxide-eugenol cement showed slight to moderate inflammatory reactions with two cases of a severe reaction at 30 days without bacterial invasion. The Graft LC resin with the glass-ionomer lining showed none to slight responses, even less than to the zinc oxide-eugenol cement. Irritation dentin formation in response to the Graft LC was also less than that to the zinc oxide-eugenol cement. The greater reaction to the zinc oxide-eugenol cement might possibly be due to chemical irritation from the eugenol (Brännström & Nyborg, 1976; Meyron, 1985).

McComb (1982) reported that significant evidence exists to suggest good biocompatability of the glass-ionomer restorative materials, and Kimura and others (1985) reported a minimal histopathological pulpal response to amalgam restorations lined with G-C Lining Cement using human deciduous canines. However, occasional prolonged hypersensitivity and, in some cases, pulp death have been reported to occur after cementation of crowns with some glass-ionomer materials (Council on Dental Materials, Instruments, and Equipment, 1984).

Two possibilities have been proposed as a cause of pulp irritation from the glass-ionomer cement: one is bacterial leakage and another is acidity of the cement.

Schmalz, Schmalz and Rotgans (1986) and Plant and others (1988) reported a severe inflammatory response to a glass-ionomer cement restoration, which was associated with bacterial invasion. Several studies have shown that etched glass-ionomer lined composite restorations enhance microleakage as contraction stress gaps develop at the tooth-restoration interface (Fusayama, 1987; Oyamada, 1989). Bacterial invasion is a sign of separation of a restoration from the cavity walls and resulting microleakage. No bacterial invasion in the Graft LC group, however, was found in this study. Ogawa, Hsiao and Terashita (1989)

investigated the interface of floor dentin and an etched ionomer lined composite restoration and found no gaps at the cement/dentin interface when the cement thickness was more than 0.5 mm. The size of the cavity was as much as 2.5 mm in diameter and 2.0 mm in depth, and at least one-fourth of the bulk of the cavity was occupied with the lining cement in this study. Considering the volume of the composite placed in the cavity, polymerization shrinkage seems to have little effect on the adhesion of the lining cement to the dentin, resulting in better adhesion at the interface; sealing at the cavity margins was secured by resin-enamel bonding. These facts seem to contribute to negligible inflammation or irritation dentin formation and no bacterial invasion to the Graft LC resin restoration in this study.

Stanley (1990) emphasized that the glass-ionomer cement is toxic to the dental pulp only when used as a luting agent less than 0.5 mm from the pulp. The powder:liquid ratio of the G-C Lining Cement is 1:2, much thinner than the 1:4 of Fuji ionomer type I luting cement, to allow for a more fluid consistency. The pH of the lining cement 10 minutes after the start of mixing was reported to be 4.8, comparable to that of the luting cement (Yasumoto & others, 1984). The setting time of the lining cement, however, was much shorter than that of the luting cement, and dissolution of the cement by acidic treatment performed six minutes after the start of mixing was significantly less with the lining than with the luting cement (Yasumoto & others, 1984). There is some possibility that quick setting of the lining cement might suppress the acidic irritation of the cement.

CONCLUSIONS

The pulpal response to a new light-cured composite resin (which was placed in etched glass-ionomer lined cavities according to the manufacturer's instructions) was less than that to the negative control material, a zinc oxide-eugenol cement, at all time intervals. These findings suggest that covering all dentinal walls and floor with the glass-ionomer lining cement and placing a composite with an acid-etching technique causes little irritation to the pulp.

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Comparing Two Methods of Moisture Control in Bonding to Enamel: A Clinical Study

N BARGHI • G T KNIGHT • T G BERRY

Summary

Twelve patients provided a total of 36 teeth to be used in this study. Visible-light-cured composite resin tabs were applied to a flattened, acid-etched surface of each tooth. Half of the teeth were isolated with cotton rolls in conjunction with a saliva ejector; the other half were isolated using a rubber dam. An equal number of teeth were treated in each group for each subject to serve as a self-control. After extraction the teeth were mounted and shear bond strength of the composite resin to enamel was determined on an Instron Testing Machine. There was a significant difference in the shear bond strength between the two experimental groups.

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Introduction

Bonded restorations have become increasingly more popular as research and clinical results have demonstrated their benefits and longevity, and as new materials and methods have been developed to enhance their physical properties and durability. Although the existence of intraoral factors has raised doubt about obtaining perfect adhesion in the mouth, clinical and laboratory studies suggest that adhesion to enamel could be optimized by proper pretreatment of enamel and controlling surface contamination (Berry & others, 1990). Young and others (1975) as well as Hormati, Fuller and Denehy (1980) have reported moisture contamination of acid-etched enamel as a major factor which can significantly affect the adhesion between enamel and the composite resin. Silverstone (1984) stated that the single most important requirement for achieving good bonding after etching the surface is the application of resin to an etched surface which has not been contaminated with saliva. Several

studies have demonstrated the adverse effect on bond strength that occurs when the etched surface is contaminated prior to placement of the composite resin (Young & others, 1975; Hormati & others, 1980; Glantz, 1977; Evans & Silverstone, 1981; Beech, 1978; Von Fraunhofer, 1979). Young and others (1975) reported a 70% reduction in bond strength when testing pit and fissure sealants placed on a contaminated etched surface versus sealants placed on a noncontaminated surface. Silverstone (1984) demonstrated that a period as brief as one second of exposure to freshly collected saliva can result in formation of a very tenacious surface coating which cannot be adequately removed by a washing regimen alone. Re-etching is necessary to restore the surface to the proper condition for bonding. His study supports other studies showing that a film of organic pellicle quickly forms on etched enamel surfaces (Glantz, 1977; Kastendieck & Silverstone, 1979; Garberoglio & Cozzani, 1979). This film prevents proper adhesion contact between composite resin and etched surfaces. SEM studies demonstrate that saliva contamination of the etched surface actually affects the morphological characteristics of the surface and that the proteins in the saliva block many of the micropores which were formed during the etching process (Hormati & others, 1980). In vitro studies which determined the shear bond strength of composite resin to enamel which had been etched and then exposed to saliva and other contaminants have exhibited a considerable decrease in bond strength in the group with a saliva-contaminated surface as contrasted with the group exposed to other contaminants (Young & others, 1975; Hormati & others, 1980).

The effect of saliva contamination on adhesion of composite resin to enamel is reported to be multifold. Glyco-proteins in saliva actually plug the micropores in the enamel that were created by the etching process (Hormati & others, 1980), so entry of the resin into the micropores to establish mechanical retention is prevented to some degree. In addition, saliva acts as a film barrier at the contact level between resin and the enamel and also lowers the surface energy of the enamel, which inhibits good adhesion. Diffusion of water from the contaminated surface in composite resin also has an adverse effect on bond strength. All these problems make it apparent that moisture control is absolutely necessary during the entire procedure from the time of etching through the curing of composite resin. Intermittent moisture control with episodes of careful drying to make up for brief moisture contamination does not appear to produce acceptable bond strengths.

A rubber dam is considered the best means for moisture control for the etched surfaces. Its use is heavily emphasized by dental schools for a variety of clinical procedures, including bonding to enamel. In spite of this, practitioners often disregard using a rubber dam to prevent moisture contamination. Surveys have shown that the use of a rubber dam by dentists decreases as the number of years postgraduation increases (Hagge & others, 1984; Wolcott & Goodman, 1964). Most restorative procedures, except for class 5 restorations, are commonly placed without rubber dam isolation. While dental institutions continue their emphasis on the use of a rubber dam as the primary means of moisture control, its use has declined among dentists who graduated after 1980 compared with those who graduated before 1970 (Hagge & others, 1984). This is despite the increasing popularity of bonded restorations, which require proper moisture control to achieve optimal bond.

In spite of the high correlation reported between the clinical instruction and the use of rubber dams (Wolcott & Goodman, 1974), manufacturers have not consistently emphasized the use of a rubber dam for procedures requiring moisture control. In the absence of clinical studies to correlate with laboratory studies showing the effect of proper moisture control on bond strength of composite resin to etched surfaces, reluctance exists for the use of a rubber dam during bonding procedures. This in vivo study was designed to measure and compare the bond strength of composite resin to enamel with the rubber dam and without the rubber dam (using cotton rolls and a saliva evacuator device).

Materials and Methods

Patients requiring multiple extractions of the posterior teeth were recruited from the previously treatment-planned patient population of the Outpatient Clinic at The University of Texas

Health Science Center at San Antonio Dental School. Pregnant patients or patients with a medical history which would place them in the Dental School's special patient care category were excluded from the study. Multiple extractions allowed the investigators to test the efficacy of both methods for moisture control on each patient, thus controlling individual variables such as enamel, home care, and other oral conditions. This experimental design also facilitated better data comparison of the two methods on each patient and between all patients (Table 2). Posterior teeth were chosen because the likelihood of contamination of the etched surfaces with saliva after etching and before bonding seems greater on these teeth.

Table 2. Comparison of Shear Bond Strength (MPa) of Composite Resin to Enamel Using the Two Methods of Moisture Control on Each Patient

Patient	Tooth #	Rubber Dam Isolation (MPa) Bond Strength (MPa)	Tooth #	Cotton Roll Isolation Bond Strength (MPa)
1	19	16.56	12	16.30
	20	15.50	13	10.60
2	1	23.18	32	21.86
3	12	17.09	2	9.80
	13	16.30	19	12.85
			30	17.75
4	16	15.63		---
5	14	19.08	3	12.59
6	3	13.91	5	16.16
	4	16.16	12	15.90
7	32	14.04	1	7.15
8	17	17.89	1	15.10
	32	21.99	16	8.48
9	1	13.25	16	9.67
10	31	27.42	6	15.24
11	19	25.44	20	19.87
12	28	28.88	22	23.05

Thirty-six teeth with intact (caries- and restoration-free) facial surfaces were utilized for this study. Isolation for moisture control was performed on 18 teeth with the use of a rubber dam (The Hygenic Corporation, Akron, OH 44310) and on the remaining 18 teeth with the aid of cotton rolls and a saliva-evacuator device. A FG-835C diamond wheel (Teledyne Getz, Elk Grove Village, IL 60007) with a diameter of 5 mm was employed to flatten the facial surfaces of all teeth (Fig 1). Prepared surfaces were etched with 37% orthophosphoric acid for 60 seconds and then thoroughly rinsed for 20 seconds with water. After drying with oil-free air from an air syringe, surfaces were visually examined to assure adequate etching. Every effort was made to protect the etched surfaces from saliva contamination when the cotton roll technique was utilized. Etched surfaces were rinsed and dried, cotton rolls demonstrating any wetness were carefully replaced with dry ones, and care was taken to retract the cheek from the operative site. Immediately after assuring that the etching was sufficient, the unfilled resin (Scotchbond Dual Cure Dental Adhesive, 3M Dental Products, St Paul, MN 55144) was lightly applied with a brush to the etched surface and thinned with a light blast

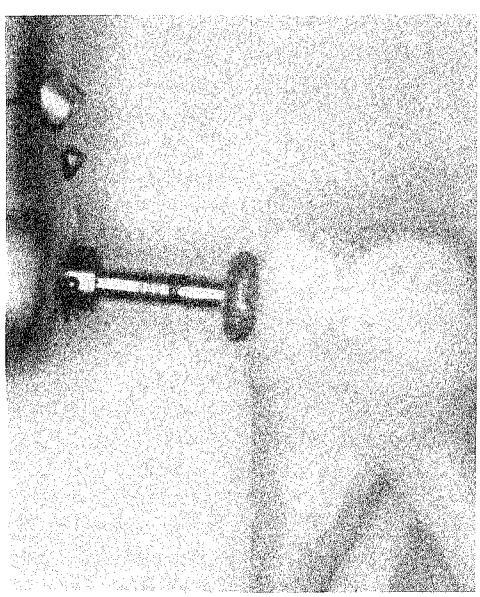

FIG 1. *In vitro representation of the clinical procedure demonstrating flattening of the buccal surface of the upper molar with a diamond wheel*

of air. The unfilled resin layer was light-cured for 20 seconds with a visible-light-curing unit (Command, Sybron/Kerr, Romulus, MI 48174).

A teflon tube with an internal diameter of 3.1 mm and a height of approximately 2 mm was slightly overfilled with a microfill composite resin (Silux, 3M Dental Products) and placed onto the flattened surface covered with unfilled resin. After placement the composite resin was light-cured 30 seconds at the opening of the tube and 20 seconds on each peripheral side for a total of 110 seconds to assure complete curing of the material. When the curing was completed, the tube was carefully removed, leaving a composite resin cylinder approximately 2 mm long and 3 mm in diameter bonded to the facial surface of each tooth. To minimize possible discomfort to the patient, the length of the resin cylinder was reduced to 1 mm using a diamond wheel. The sharp angle at the outer end was also rounded. The total bonded area of the composite resin to enamel was 7.5 mm^2.

The selection of the initial isolation method (rubber dam or cotton rolls) was made on a random basis for each patient. To minimize operator variables, all tooth preparations and placement of composite resin rods were performed by one clinician. A code number was assigned to each tooth to decrease the possibility of any bias.

Approximately two weeks after placement of the composite resin, the teeth were extracted by an oral surgeon (Fig 2). The surgeon was informed of the presence of the composite resin cylinder, so care was exercised to avoid any possible damage to the bonded composite resin. Immediately after extraction the teeth were stored in normal saline solution.

Within a five-to-seven-day period, extracted teeth were mounted in stone blocks, using a mounting device which positioned the flattened surface of the tooth perpendicular to the base (Figs 3 & 4). An Instron Universal Testing

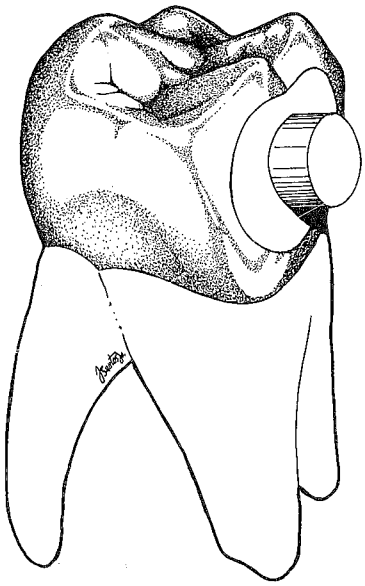

FIG 2. *Schematic view of an extracted upper molar tooth with bonded composite resin*

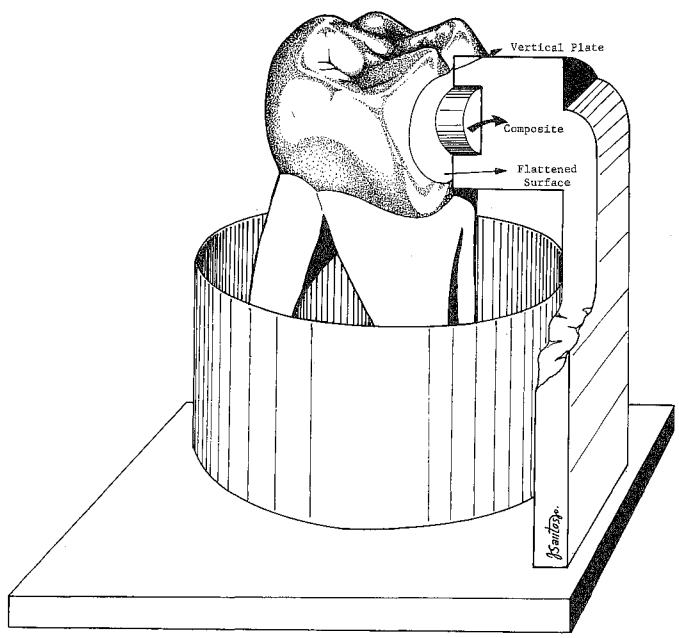

FIG 3. *Schematic view of a device used to mount the extracted teeth. The vertical plate of the device and the flattened surface of the tooth allow for the proper orientation and mounting.*

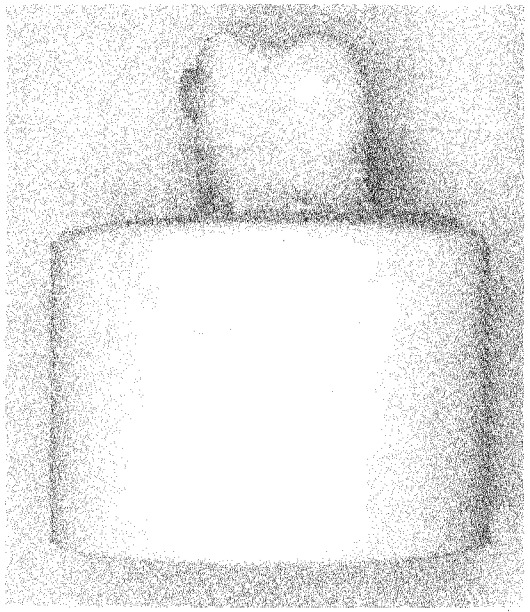

FIG 4. *An upper molar with bonded resin mounted in a stone block*

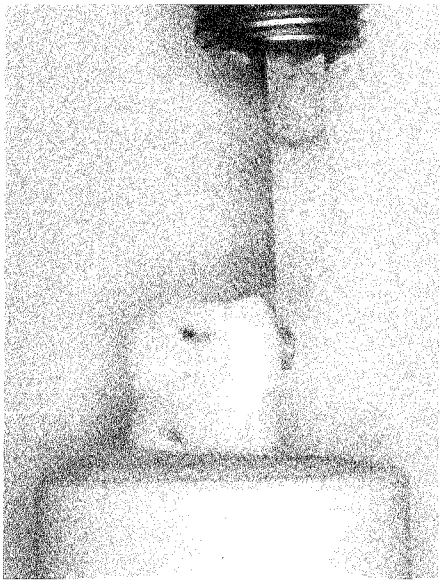

FIG 5. *A mounted specimen subjected to shear bond test with an Instron machine*

Machine (Instron Corp, Canton, MA 02021) with a crosshead speed of 1 mm/min was used to test the shear bond strength of composite resin to enamel. A flat shear blade positioned perpendicular to the composite resin was used (Fig 5). The point at which the resin was sheared from the enamel was recorded as the shear bond strength. Visual examination was used to determine the mode of the fracture. Data were recorded and subjected to a two-tailed, paired *t*-test. A desired alpha level of 0.05 was established as the level of significance.

Results

Table 1 depicts the mean and standard deviation for shear bond strength for the two experimental groups. Data are reported for 16 specimens on each group. Two specimens (one from each group) fractured during extraction and two specimens (one from each group) experienced technique problems.

The results show a mean bond strength of 18.895 MPa for the specimens placed with a rubber dam in place and a mean of 14.523 MPa for those placed without a rubber dam, with a mean difference of 4.372. Analysis of the data revealed a paired *t*-value of 3.925, with a probability level of 0.0014. A statistically significant difference was observed between the shear bond strengths of the two experimental groups.

It was difficult to make an exact determination of the mode of fracture when it was adhesive. Under a low magnification one can always detect the residual resin tags remaining on the etched interface of the tooth. The cohesive mode of fracture (occurring primarily within the body of the composite resin layer) was recorded 45% of the time for rubber dam specimens and 25% for cotton roll specimens. It is important to note that most of the fractures for both groups were varying mixtures of adhesive and cohesive fractures.

Table 1. Overall Comparison of Shear Bond Strength (MPa) of Composite Resin to Enamel Using the Two Methods of Moisture Control

Group	Mean (MPa)	SD
Rubber dam isolation	18.895	±4.964
Cotton roll isolation	14.423	±4.710

Discussion

Results of this in vivo study support the findings of the previous in vitro studies demonstrating that contamination of the etched surfaces with saliva significantly affects the adhesion of composite resin to enamel. Despite every effort to keep the etched surface dry during the bonding procedure, the bond strength was significantly lower for teeth bonded to composite resin while using cotton roll isolation.

The mean bond strength of composite resin to etched enamel obtained in vitro and reported previously (Berry & others, 1990) is greater than 22 MPa,which is markedly higher than the results of this in vivo study. Similarly the mode of fracture seems to be noticeably different for in vitro and in vivo studies. In laboratory studies the fracture mode of composite to enamel is primarily cohesive and within the enamel layer. Examination of the fracture mode in this study reveals that the nature of fracture was less cohesive for the rubber dam specimens (45%) and even less cohesive for the cotton roll specimens than in laboratory studies. Very few specimens fractured within the enamel layer. In light of these discrepancies, it becomes clear that in vitro findings do not necessarily reflect the true nature of the adhesion of composite resin to enamel that one may expect in the oral environment. These discrepancies become even greater if there is a possibility for surface contamination with saliva. The rubber dam, as indicated by this study, provides a more consistently predictable means of moisture control than do cotton rolls and an evacuation device.

Conclusions

This in vivo study evaluated and compared the bond strength of composite resin to acid-etched enamel with and without the use of a rubber dam. Cylindrical-shaped composite resin rods were bonded to teeth treatment-planned for extraction. Methods utilized for controlling moisture were: a) placement of a rubber dam and b) the use of cotton roll isolation. Following extractions bonded resins were subjected to shear bond strength testing. The following conclusions were made.

1. Overall, utilization of the rubber dam for moisture control and isolation resulted in significantly higher shear bond strength of composite resin to enamel. Results were consistent between the tested teeth of each patient and between the tested teeth of all patients.

2. The mode of fracture between enamel and composite resin may differ between in vitro and in vivo conditions. Additional studies are needed to further clarify this difference.

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Strength of Posterior Composite Repairs Using Different Composite/ Bonding Agent Combinations

A D PUCKETT • R HOLDER • J W O'HARA

Summary

Posterior composites are becoming a viable alternative to amalgam in selected cases. As the use of posterior composites increases, the necessity of repair of fractured, discolored, or worn restorations will increase. A number of studies have demonstrated that clinically acceptable repairs can be obtained for anterior composites. This study examined the bond strength of repairs made to aged posterior composite substrates when different bonding agent/composite pairs were used. Dentin bonding agent/composite pairs gave the highest bond strengths and were greater than the bond strength of resin to etched enamel. An enamel bonding agent/composite repair gave the lowest bond strengths, which were less than resin/etched enamel bond strengths.

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Introduction

The properties of composite formulations advocated for use in posterior teeth are improving and are slowly becoming accepted by the dental profession. These posterior composites have cosmetic attributes, but their placement is more difficult and time-consuming than amalgam. In addition, the current composites still exhibit problems with marginal leakage, discoloration and wear.

Because of these problems a number of investigators have examined the feasibility of repairing mature composite substrates (> 24 hours) with fresh composite. Initial studies looked at interfacial bond strengths of repairs

made to anterior composites (Causton, 1975; Boyer, Chan & Torney, 1978; Lloyd, Baigrie & Jeffrey, 1980; Chan & Boyer, 1983; Boyer, Chan & Reinhardt, 1984; Pounder, Gregory & Powers, 1987). The bond strengths of repairs ranged from 25% to 80% of the control samples depending upon materials used, surface preparation and experimental conditions. Most authors concluded that the bond strength of repairs exceeded the composite bond strength to enamel (18 MPa) and were therefore clinically acceptable.

In contrast to the body of work on anterior composites, there have been very few studies describing the repair of more highly filled posterior composites. Lloyd and Dhuru (1985) measured the immediate repair strength of an autocuring posterior composite and found that the use of a bonding agent overcame the reduction of bond strengths when the repair surface was contaminated with saliva. Eli and others (1988) investigated the repair of seven-day-old substrates of two posterior composites and found that grinding of the surface before repair reduced the repair strengths. A recent study by Crumpler and others (1989) investigated the effect of mechanical, chemical, and primer conditioning techniques on the repair strength of four posterior composites. This study concluded that mechanical reduction with a diamond bur followed by a bonding agent and composite was the optimal repair procedure.

Another area deficient in the literature is the consequences of repairing a composite substrate with a different material. In many clinical situations composition of the restoration to be repaired may be unknown. Chalkley and Chan (1986) measured the microleakage between repair procedures using different anterior products. They found that repairs involving combinations of a urethane dimethacrylate-based composite and a BIS-GMA composite leaked to a greater extent than repairs involving like materials. Lloyd and Dhuru (1985) reported interactions between products of different chemistries but concluded that they were not significant. Another study (Eli & others, 1988) found no effect on repairs when combinations of two different BIS-GMA-based composites were used. Pounder and others (1987) investigated the repair of like and unlike anterior composites using different bonding agents. Results from this study suggested that repair strengths are very hard to predict based upon the repairing resin and bonding agent alone, and that the bond strengths of repaired composite resins studied did not always reach the clinically functional strength of composite to enamel bonding.

Therefore, the objective of this study was to evaluate the strengths of repairs made to mature posterior composite substrates when composite/bonding agent combinations representing different manufacturers and chemistries were used. The ultimate goal was to address the clinical consequences of repairing a posterior composite restoration with a different product.

Materials and Methods

Three light-cured posterior composites and their bonding agents were studied. P30 (3M Dental Products Co, St Paul, MN 55144) and Herculite (Sybron/Kerr, Romulus, MI 48174) are hybrid composites containing a BIS-GMA matrix. Scotchbond and Bondlite, manufactured by 3M and Sybron/Kerr respectively, are dentin bonding agents based upon phosphate esters of BIS-GMA. Occlusin (Coe Laboratories, Inc, Chicago, IL 60658) is a hybrid composite containing a urethane dimethacrylate resin. The bonding agent supplied with Occlusin is an unfilled resin which is also based upon a urethane dimethacrylate.

Four different repair procedures were investigated for each composite tested as follows:

1. repair of the surface with the same material with no bonding agent,
2. repair of the surface with the same material and its bonding agent,
3. repair of the surface with one of the other composite/bonding agent pairs, and
4. repair of the surface with the remaining composite/bonding agent pair.

A diametral tensile test was used to assess the interfacial bond strengths of the repairs. This method has been shown to be valid for the evaluation of the tensile strength of dental composites (Penn, Craig & Tesk, 1987). The diametral method was chosen for its simplicity and its ability to concentrate the forces at the repair interface. Diametral tensile specimens were fabricated using ADA Specification #27. The mold consisted of a stainless steel disk

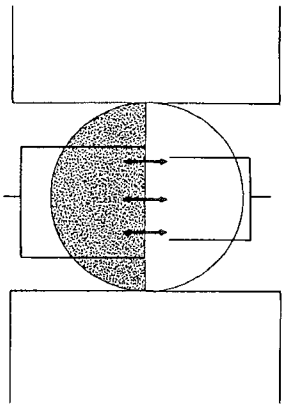
with a cavity 6 mm in diameter and 3 mm in depth. The mold was placed on a glass cover slip. Composite paste was condensed into the mold and covered with another glass cover slip. Sufficient material was placed in the mold so that it was filled completely and a small amount of flash formed. The mold was turned over and additional material was added to ensure the mold was packed completely. A Command Curing Unit (Sybron/Kerr) was used to cure the specimen for 30 seconds on each side. The glass cover slip was removed and the flash was ground away using wet 400-grit paper. Samples were ejected from the mold, placed in a container of Ringer's solution, and stored in a constant-temperature oven at 37 °C for 24 hours. Ten specimens were prepared for each repair procedure.

After aging, 10 specimens for each material were tested to obtain the diametral tensile strength of the composite to serve as control. Other specimens from each material were ground to one-half their original dimensions (3.0 ± 0.1 mm) using wet 240-grit paper to form the substrate for repair procedures. After grinding, the substrate was washed for 30 seconds with tap water then blown dry for 30 seconds with compressed air.

When no bonding agent was employed, the ground dry substrate was placed back into the mold. Additional composite was packed into the mold and cured as described earlier. When a bonding agent was used, the bonding agent was brushed on, blown thin with compressed air, and light-cured according to the manufacturer's instructions. The sample was then placed back into the mold and fresh composite added and light-cured. The samples were placed in Ringer's solution and stored at 37 °C for 24 hours before testing.

The diametral tensile tests were carried out as given in ADA Specification #27. The tests were conducted on an MTS Model 870 (MTS Systems Corporation, Minneapolis, MN 55424) servohydraulic testing apparatus. The rate of testing was 1 cm/minute. Diametral tensile strengths were calculated using the following equation: DTS = 2P/td.

DTS is the diametral tensile strength, P is the breaking force, d is the diameter of the specimen (6 mm), and t is the thickness (3 mm).



Drawing to illustrate the diametral tensile test. One-half of sample was shaded so that the repair interface could be centered normal to the tensile stress when placed under a compressive load.

To facilitate alignment of the test specimen, the repair substrate was marked with a graphite pencil. In this way the repair line could be visually centered normal to the compressive load as shown in the figure.

Results

Filler loadings supplied by manufacturers and the measured diametral tensile strengths of the composites investigated are given in Table 1. The measured bond strengths of the various repair combinations are given in Table 2. The repair bond strengths ranged from 20% to 60% of the diametral tensile strength of the composite materials. All failures occurred at the repair interface. Results were evaluated using

Table 1. Properties of Composite Resins

	Filler Loading by Weight (%)	Filler Loading by Volume (%)	Diametral Tensile Strength (MPa)
Occlusin	85.9	69	54.8 ± 3.4
Herculite	76 - 78	57	37.7 ± 6.6
P30	86 - 88	70	52.8 ± 4.7

Table 2. Bond Strength of Repairs by Bonding Agent/Composite Pair

	No Bonding Agent Mean SD (MPa)	Occlusin/Bonding Agent Mean SD (MPa)	Herculite/Bondlite Mean SD (MPa)	P30/Scotchbond Mean SD (MPa)
Occlusin	17.0 ± 3.6	18.2 ± 6.5	29.1 ± 6.1	23.0 ± 5.0
Herculite	10.4 ± 4.2	12.1 ± 4.3	21.5 ± 3.6	25.9 ± 6.8
P30	12.7 ± 3.7	12.8 ± 3.1	18.1 ± 8.5	23.5 ± 4.7

Horizontal lines connect groups that are not statistically different according to a Newman-Keuls test; $\alpha = 0.05$ (n = 10).

analysis of variance (ANOVA) and the Newman-Keuls test for significance.

For Occlusin, the highest repair strength was obtained using the Herculite/Bondlite combination, but there was no statistical difference between any of the repairs when a bonding agent was used. All the repairs using a bonding agent were significantly better than those using no bonding agent.

For Herculite, the P30/Scotchbond combination gave the highest bond strength, with the Herculite/Bondlite combination only slightly less. Repairs made with these materials were significantly better than those made with the Occlusin/Bonding Agent combination or when no bonding agent was used. An interesting result was the fact that the repair made with the Occlusin/Bonding Agent combination had essentially the same strength as the repair using no bonding agent.

The results for P30 were very similar to those obtained for Herculite. The P30/Scotchbond combination again gave the highest repair strength, with the Herculite/Bondlite combination slightly less. The repairs made with these materials were significantly better than those obtained using the Occlusin/Bonding Agent or no bonding agent. Once again the mean bond strength of the repair made with the Occlusin/Bonding Agent combination was nearly the same as the strength of the repair when no bonding agent was used.

A microscopic inspection at X40 of the fracture surfaces of the P30 and Herculite substrates repaired with Occlusin suggested that the failure of the bond in these instances is predominately adhesive. The examination revealed that there was very little adhesive retained on the repair substrate, and the abraded surface of the substrate was clearly visible. On all other fracture surfaces, including those where Occlusin was repaired with the BIS-GMA materials, composite and bonding agent were clearly visible, indicating a mixed cohesive and adhesive failure.

Overall Occlusin consistently gave the highest repair strengths when used as a substrate, but the lowest repair strengths when used as the repair material. Herculite and P30 performed approximately the same as a substrate and repair material.

Discussion

The repair of all substrates with the Occlusin bonding agent/composite combination gave significantly lower bond strengths than the other combinations. The lower bond strengths may be due to a number of factors, including wetting ability and chemistry.

Wetting of the substrate by the repair material is a major factor controlling the repair bond strength. Wetting is controlled by the surface free energy differences between the substrate and bonding resin and the viscosity of the bonding resin. In this study the enamel bonding agent appeared to have a significantly higher viscosity than the dentin bonding agents. Therefore its ability to wet the repair surface and penetrate the exposed organic

phase would be less. In addition, for these highly filled posterior composites, the surface is primarily exposed inorganic phases. The establishment of strong chemical bonds to the inorganic phases using the enamel bonding resin is not possible without the use of a coupling agent (Söderholm, 1985). Consequently the primary chemical bonding obtained when the enamel bonding resin is used for repairs is through reaction of the resin with residual unsaturated species in the substrate. Additional bonding may occur if the resin is able to penetrate into the substrate where it polymerizes to form molecular entanglements.

In contrast the chemistry of the dentin bonding agent may be such that it is possible to get strong secondary bonding to the inorganic phases of substrate. The dentin bonding agents are based on chloro-phosphate esters of the BIS-GMA with a surfactant and solvent added. The phosphate group may have the ability to hydrogen bond or condense with exposed silanol functional groups in the inorganic phase. These possible reactions and the presence of a surfactant and solvent to improve wetting and penetration would explain the higher repair bond strengths when the dentin bonding agents were used.

The suggestion that additional bonding is taking place between the dentin bonding agents and the inorganic phase is supported by the lack of a dependence of bond strengths on filler loading. Herculite possesses the lowest filler loading and therefore should have more exposed organic phase available for bonding. However, the best substrate for repair overall was Occlusin, and there was not a significant difference between the repair strengths to Herculite and P30.

Conclusions

1. The highest repair strengths were obtained when BIS-GMA/dentin bonding agents were used as the repair material for both BIS-GMA and urethane dimethacrylate substrates.
2. All repairs to the urethane dimethacrylate substrates resulted in clinically acceptable bond strengths.
3. Repair of the BIS-GMA substrates with no bonding agent or the urethane dimethacrylate/composite/enamel bonding agent combination resulted in nonclinically acceptable bond strengths.

Acknowledgements

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Adhesion of Glass-Ionomer Cement in the Clinical Environment

G J MOUNT

Summary

This paper discusses the literature concerning the development of an ion-enriched layer between the glass-ionomer cement and tooth structure. Two restorations that had been in the oral cavity for considerable periods of time were used to confirm the existence of this layer. It is suggested that development of the layer is dependent on careful adherence to the recommendations for clinical placement, and recognition of the need to clean the surface of the cavity and to maintain the water balance of the cement. Having developed the ion-exchange layer, failure will be cohesive in the cement itself. Thus the strength of the union is dependent on the tensile strength of the cement.

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Introduction

There has been considerable discussion in the literature on the subject of adhesion and the potential for microleakage with the use of glass-ionomer cements. On the one hand there are a number of articles supporting their use for restorations, showing that long-term adhesion to dentin and enamel can be expected with a high level of confidence. Color stability and abrasion resistance is high, tissue tolerance is satisfactory and there have been no clinical reports of marginal leakage and recurrent caries (Mount, 1981; Aboush & Jenkins, 1986; Osborne & Berry, 1990; Tay & Lynch, 1990a,b; Wilson & McLean, 1989).

On the other hand, there have been numerous articles showing marginal leakage in vitro with the inference that failure in the oral cavity should be expected (Barakat, Powers & Yamaguchi, 1988; Cheung, 1990; Mathis & others, 1990; Crim & Shay, 1987; McInnes, Perkins & Weinberg, 1990; Scherer & others, 1989). However, many of these articles do not show a proper understanding of the chemistry or physical properties of the glass-ionomer

cements. The experimental methodology subjects them to early hydration or dehydration. Extracted human teeth or bovine dentin are used as the substrate, and the positive dentinal fluid flow experienced in the oral cavity is absent, leading to possible dehydration of the cement before it is set. Testing for tensile strength is often conducted only 24 hours after placement, before the cement has achieved its optimum properties, and often the cement is hand-mixed at low powder/liquid ratios, resulting in reduced tensile strength. Finally, the failed restoration is not examined under the scanning electron microscope to determine the nature of the failure.

There is also controversy over whether to clean the cavity and remove the smear layer prior to placement of the cement with the two views diametrically opposed to each other (White, Beech & Tyas, 1989; Mount, 1989b; Hamlin, Lynch & Samarawickrama, 1990; Duke, Philips & Blumershine, 1985). However, there do not appear to be any reports of a properly structured clinical series demonstrating a difference in the results with or without conditioning.

The chemical and physical nature of the glass-ionomer cements has been thoroughly researched, and there would seem to be a clear understanding of the relatively slow setting reaction which continues for long periods of time, with final maturity in the restorative aesthetic cements taking several months (Wilson & McLean, 1989). The fact that, with the exception of the resin-based cements, all cements by definition are water-based and are therefore subject to water loss and water uptake during their early setting reaction is clearly understood. This is certainly the case for the glass-ionomer cements.

The nature of the ionic exchange between the cement and adjacent tooth structure has been explored and a logical hypothesis has been offered. Wilson, Prosser and Powis (1983) showed that there is potential for developing an ion-enriched layer in the cement at the interface between the cement and tooth structure, and the presence of this layer has been demonstrated in laboratory investigations. The opportunity for demonstrating this layer in vivo does not occur often, but if it does in fact develop it would support the in vitro experiments and the hypothesis that chemical union is available in the clinical situation, and thus clinical procedures should be used which will encourage its development. The presence of this layer would also suggest that, as failure is generally recognized to be cohesive in the cement rather than adhesive at the interface, every effort should be exerted to achieve the highest possible tensile strength in the glass-ionomer cement for any particular restoration.

This paper investigated two glass-ionomer cement restorations in vivo. These restorations had been in the oral cavity for a substantial period of time and were placed in the normal course of clinical practice using techniques widely advocated and approved (Mount, 1981; Mount, 1989b; Wilson & McLean, 1989; Tay & Lynch, 1990a).

Materials and Methods

A class 5 erosion lesion at the buccal gingival margin of an upper right first permanent molar (Fig 1) was restored with Ketac-fil (ESPE, Seefeld, Oberbay, Germany). The cavity was lightly scrubbed with a slurry of pumice and water and conditioned for 10 seconds with 10% polyacrylic acid (G-C Industrial, Tokyo, Japan). It was thoroughly washed and dried but not dehydrated, and the cement was placed immediately with a Hawe cervical matrix (Hawe-Neos Dental, Gentilino, Switzerland) to adapt the cement to the tooth. Immediately after the

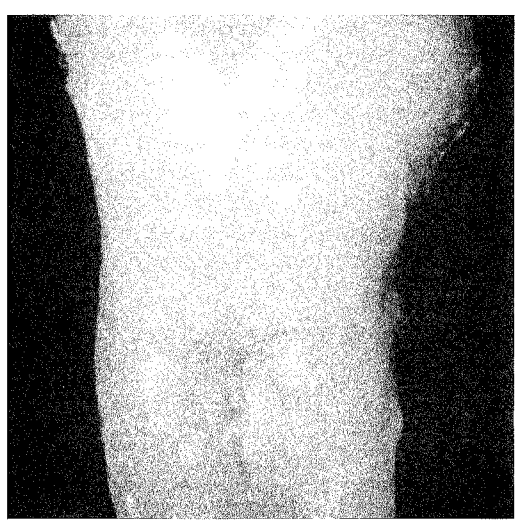

FIG 1. *Upper right first molar, extracted for periodontal reasons, showing a large class 5 glass-ionomer cement restoration (Ketac-fil) at the buccal gingival margin that was placed two years prior to extraction*

cement had achieved its initial set, the matrix was removed and the surface was painted with a liberal coating of a very low viscosity, single-component, light-activated, resin bonding agent (Visio Bond, ESPE). Excess cement was trimmed as required using a sharp blade. Additional resin bond was painted over to ensure a complete coating, and it was light-activated. The restoration did not require polishing subsequently. At the time of restoration the tooth was over-erupted and moderately periodontally involved. Two years later it was decided that, as part of an overall rehabilitation program, the tooth should be removed. Following extraction the tooth was immediately stored in tooth-preserving fluid, and shortly thereafter it was mounted in Biopot (Bond Plastics, Thebarton, South Australia) in preparation for sectioning.

The second restoration investigated was in a lower right third molar with a moderately extensive carious lesion on the occlusal surface (Fig 5). The tooth was not under occlusal load, but the patient was not anxious to have it extracted. The caries was removed by conventional means, the cavity conditioned for 10 seconds with 10% polyacrylic acid, and Ketac-Silver (ESPE) syringed into place. The cement was placed in two increments and each increment in turn was tamped into place with a small plastic sponge. The cavity was overfilled and a soft tin foil matrix was placed under finger pressure to ensure adequate condensation and to minimize the incorporation of porosities and voids. Approximately five minutes from the start of mix the matrix was removed and the cement was immediately contoured and polished at slow speed under air/water spray using fine sintered diamond stones and rubber abrasive points. Five years later, following a periodontal abscess, the patient agreed that extraction was justified. Again the tooth was immediately stored in tooth-preserving fluid until such time as it could be mounted in Biopot.

Both teeth were sectioned once buccolingually through the center of the restoration (Figs 2 & 5). Both sides of the specimens were lightly polished on wet and dry emory paper to a fine-grit size. One side of each tooth was then prepared for viewing under the scanning electron microscope, which necessitated complete dehydration of both the tooth and the cement. Replica impressions

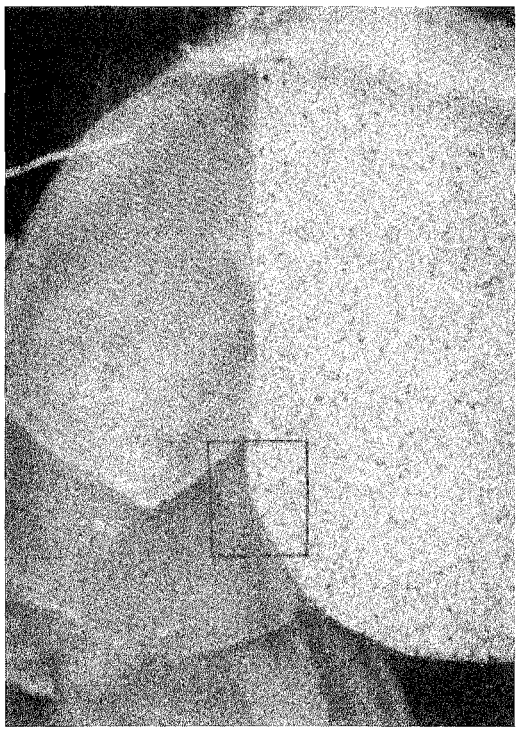

FIG 5. *A section through a Ketac-Silver restoration that was placed in a lower third molar five years prior to extraction of the tooth for periodontal reasons. Note the excellent adaption of the cement to both enamel and dentin with no sign of microleakage. The area outlined is shown magnified in Fig 6.*

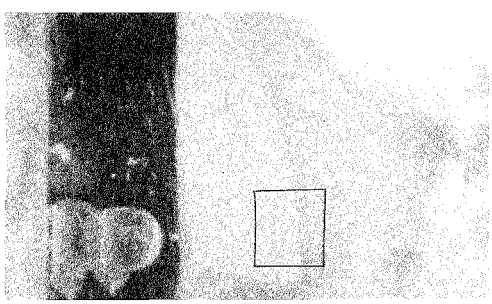

FIG 2. *The tooth has been sectioned buccolingually through the center of the restoration. Note that there is no sign of microleakage or recurrent caries nor any evidence of further abrasion on the surface of the cement. The area outlined is shown magnified in Figs 3 & 4.*

were taken of the other side, using Permagum (ESPE) as the impression material. The first impression was discarded, as it was expected to remove surface debris. After the second impression the surface of the specimen was etched with 37% orthophosphoric acid for 30 seconds, washed thoroughly and dried lightly before taking a third impression. The second and third impressions of each specimen were prepared for viewing under the scanning electron microscope (Fig 4).

Results

The two specimens which were prepared for direct viewing under the scanning electron microscope showed dehydration of the cement with extensive cracking. The cracks occurred as cohesive failure within the cement. A layer of cement, firmly adhered to both dentin and enamel, could be traced through most of the tooth/cement interface with very few areas suggesting adhesive failure (Figs 3 & 6). However, there were a number of very small porosities visible, particularly within the Ketac-Silver, and some of these were associated with areas of adhesive failure.

The replica impressions, both etched and unetched, showed a continuous union between tooth structure and cement (Fig 4). There was no sign of marginal leakage or lack of union anywhere along the interface with either restoration. Porosities in the cement were more clearly visible in the specimens which had been etched.

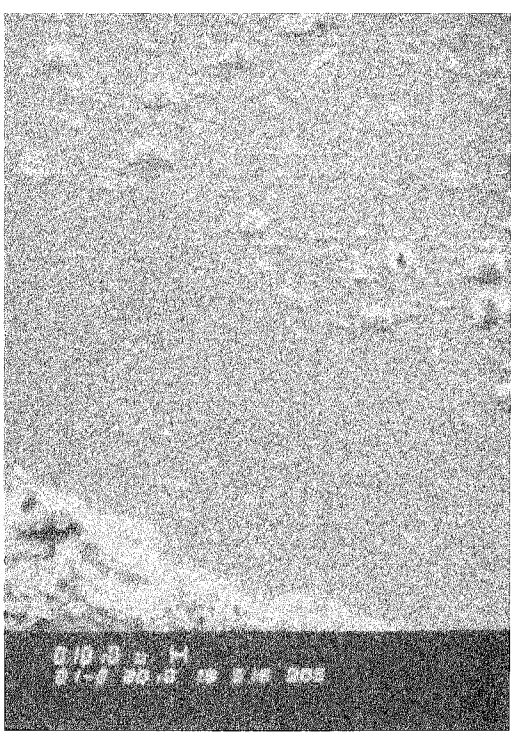

FIG 4. *To avoid artifacts resulting from dehydration, a replica impression was made of the other side of the same specimen and prepared for viewing under the SEM. Note the continuous union between the cement and the tooth structure with no sign of microleakage.*

Discussion

The results observed with these two clinically placed restorations coincide with observations made during in vitro experiments (Tay & Lynch, 1989; Aboush & Jenkins, 1986). The basic chemistry of the setting reaction of glass-ionomer cement has been detailed by a number of authors (Smith, 1990; Wilson & McLean, 1989; Mount & Makinson, 1982). Wilson and others (1983) point out that the reaction is extremely complex and is not precisely understood. However, there is adequate information for the development of clinical techniques that will succeed. The continued clinical use of the cement is indeed warranted.

The development of the ion-enriched layer of cement on the surface of the enamel and dentin is of paramount importance in the retention of the glass-ionomer cement and to prevent microleakage. Hotz and others (1977) first proposed an ion exchange, but admitted that the mechanism was not entirely clear. Later Causton and Johnson (1979) suggested the formation of an intermediary layer which became a cement in its own right, consisting of precipitated components from both sides of the interface, rather like a weld. They were the first to note that failure is generally cohesive in the cement, leaving a residue on the dentin which could be seen under the scanning electron microscope. This has subsequently been confirmed by other authors. Causton went on to point out the possibility of continuing diffusion of ions from the dentin surface for a considerable length of time following the initial set.

Subsequently, Wilson and others (1983) refined these theories and demonstrated an ionic exchange by interacting hydroxyapatite with polyacrylate ions and actually measuring the

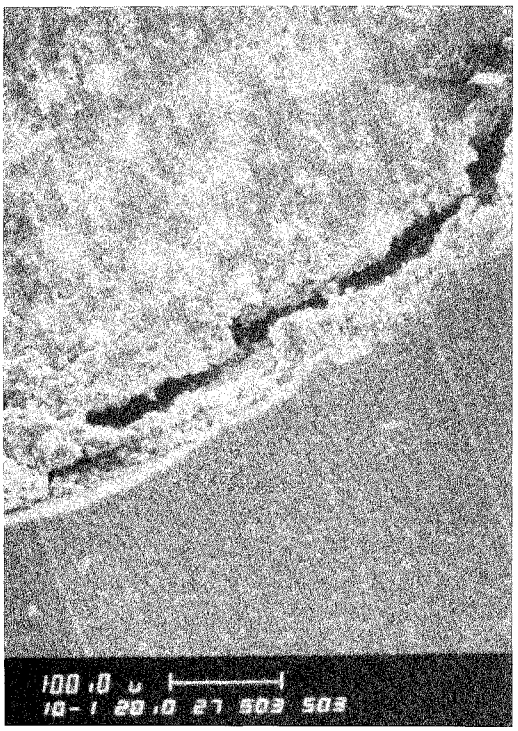

FIG 3. *The area outlined in Fig 2, magnified X75 under the SEM, showing the glass-ionomer cement still attached to the dentin with cohesive failure in the cement. Based on the Wilson hypothesis, the attached cement represents the ion-enriched layer. Note that the cement has cracked because of dehydration during preparation for examination under the SEM.*

transfer of ions into solution. They showed that polyacrylate ions strongly integrate with and become irreversibly attached to hydroxyapatite by displacing phosphate and calcium ions from its surface. For stereochemical reasons only one CO_2^- group can replace a PO_4^{3-} group on the surface of the hydroxyapatite. If electrical neutrality is to be maintained, then each displaced PO_4^{3-} group must be accompanied by a Ca_2+ ion. Thus the surface layer of the adhering cement becomes enriched in phosphate and calcium ions as these diffuse from the enamel or dentin surface (Fig 7). Additionally, there may be other types of ionic exchange across the interface, mainly of cations, and this would explain the intermediate layer of ion-enriched cement which can be seen under the scanning electron microscope.

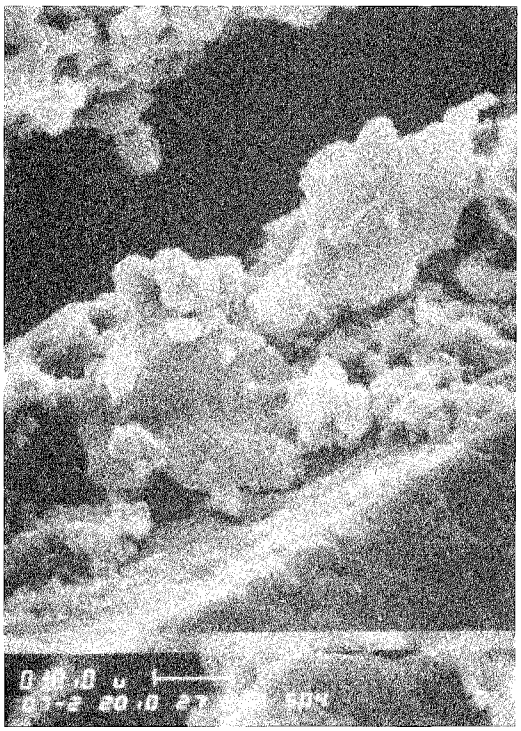

FIG 6. *The area outlined in Fig 5, magnified X525 under the SEM, showing the cement still attached firmly to the enamel and dentin with cohesive failure in the cement. Note that the cement has cracked because of dehydration during preparation for examination under the SEM.*

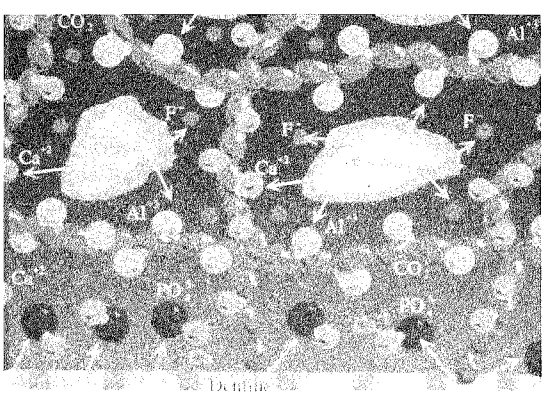

FIG 7. *A diagrammatic representation of the Wilson hypothesis. As the surface of the glass particles is softened by the polyalkenoic acid, calcium ions are released to form calcium polyacrylate chains. Subsequently aluminum ions follow the same pattern, forming aluminum polyacrylate chains, and fluoride droplets are released and lie free within the newly forming matrix. When the freshly mixed cement is placed on enamel and dentin, phosphate ions in the tooth surface are displaced by the polyacrylate chains. Each phosphate ion takes with it a calcium ion, and the result is an ion-enriched layer firmly adherent to the tooth structure and with greater physical properties than the parent cement.*

Although there may well be further details of this ionic exchange to be defined, it is apparent that this is essentially the mechanism by which glass-ionomer cements adhere to tooth structure. Since failure under these circumstances is primarily cohesive in the cement itself, it is clear that the true strength of adhesion has yet to be measured. Experiments to date have measured only the tensile strength of the cement, rather than the strength of the tooth/cement interface. Variations in adhesion with the same cement following various surface treatments indicate either alteration to the tensile strength of the cement by changing the powder/liquid ratio(Billington, Williams & Pearson, 1989; Welbury & Murray, 1990), interference with the ionic exchange by dehydration of the cement (Wilson, Paddon & Crisp, 1979), or the presence of foreign material at the interface.

There is therefore a logical assumption that increasing the tensile strength of glass-ionomer cements will increase the apparent strength of the union between the cement and tooth structure. Mount (1989a) showed that the use of capsulated cements with a powder/liquid ratio of 3:1 or higher resulted in notably increased resistance to fracture in the union between composite resin and glass-ionomer cement. It is clear from that report that, regardless of methods of surface treatment, cements that are hand-mixed and contain a low powder content have a low tensile strength. The only exception at present is a light-activated glass-ionomer lining cement, and in this material it is the resin content which enhances the tensile strength. Current clinical studies of longevity of restorations which have been mixed with a high powder/liquid ratio and have been placed without undue occlusal load suggest that the present cements possess adequate tensile strength to withstand displacement under these limited circumstances. Thus the primary objective of increasing tensile strength would be to enhance the success of glass-ionomer cements when subject to occlusal stress, such as in the restoration of a marginal ridge.

Controversy over the need to clean the surface of the cavity by so-called "conditioning" prior to placement of the cement appears to revolve around two points. Beech, Solomon and Bernier (1985) and White, Beech and Tyas (1989) consider it highly undesirable to chemically leach the surface of the newly prepared cavity, as it could intefere with the development of the ionic exchange layer through unnecessary removal of calcium or phosphate ions. They also suggest that retention of the smear layer will leave plugs in the dentinal tubules and so prevent a positive dentinal fluid flow. In vitro this appears logical. However, in vivo the composition of the smear layer is far more complex, and it contains more than debris produced by instrumentation (Mount, 1989b). It would seem undesirable to leave remnants of plaque, pellicle, saliva, and possibly blood, as well as the smeared enamel and dentin, to complicate the development of the adhesive layer. A compromise is probably the best solution, where a brief 10-second application of a 10% solution of polyacrylic acid is applied, followed by thorough washing and a very brief period of drying without inducing dehydration of the dentin. It has been shown that the gross debris will be removed under these circumstances, but the dentinal tubules will not be opened nor the tooth surface demineralized (Barakat & others, 1988; Aboush & Jenkins, 1987; Berry, von der Lehr & Herrin, 1987; Mount, 1989b).

There is no evidence yet from clinical surveys that such a conditioning routine will either enhance or reduce the adhesion of glass-ionomer cements. Several papers on longevity (Mount, 1986; Tay & Lynch, 1990b; Osborne & Berry, 1990) report the use of different methods of cavity cleaning, and there appears to be no difference in the success rate that could be attributed to conditioning. Clinical experience emphasizes the desirability of subjecting the freshly prepared cavity to more than simply washing with water, and the above suggestion for conditioning with polyacrylic acid is recommended when using the Type II.1 restorative aesthetic cements or when lining or basing a cavity with the Type III cements.

The only reports of postinsertion sensitivity (Klausner, Brandau & Charbeneau, 1989) arise from the luting of full crowns following lengthy conditioning (30 seconds or more) of the preparation with various agents, and this is not surprising in view of the large hydraulic forces which can be generated under these circumstances. It is suggested that the smear layer be left on the dentin of a full crown preparation

even though full adhesion through the glass-ionomer cement may not be achieved. Retention of such a restoration should be achieved through preparation design rather than the cement, which, mixed at a low powder/liquid ratio, will have a low tensile strength.

Conclusions

Examination of two restorations which were placed under normal clinical conditions shows that laboratory investigations that have suggested that the adhesion between glass-ionomer cement and dentin and enamel is the result of the development of an ion-enriched layer in the cement have substantiated this in the oral cavity. Development of this layer will depend upon proper preparation of the tooth surface, careful maintenance of the water balance of the maturing cement, and allowing time for maturation prior to testing.

As with any dental material, it is necessary to recognize and understand all of its chemical and physical properties and the speed with which these properties develop, before drawing conclusions from in vitro experimentation. Microleakage leading to recurrent caries in relation to glass-ionomer cement restorations placed in the oral cavity has not been reported. Furthermore figures purporting to record the strength of adhesion between the cement and tooth structure are in fact reporting the tensile strength of the cement itself.

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BUONOCORE MEMORIAL LECTURE

Michael Buonocore

The Science and Art of Dental Ceramics

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INTRODUCTION

It is hardly surprising that human history has been traced through work in ceramics, since this unique group of materials are remarkably resistant to corrosion, abrasion, or solution, even in strong acids. These properties led Fauchard in the early part of the 18th century to suggest the use of porcelain for making artificial teeth, and from that date work has never ceased on this attractive group of materials, leading to the highly sophisticated ceramics that are used today. New high-strength ceramics are being advocated as a replacement for the metal-ceramic restoration. However, all these materials have their limitations, particularly in relation to accuracy, fracture toughness, and maintenance of crack-free surfaces. Construction of aesthetic ceramic restorations still remains an art, and mass production methods cannot as yet replace the skills of the dental technician. Quick solutions to aesthetic problems may appear attractive initially, but long-term success should be based on well-proven methods that have become traditional because they work. The potential of resin-bonded porcelain laminates and inlays is

promising, providing the hydrolytic stability of the resin cements can be improved. The future for dental ceramics is still as bright as in the days of Fauchard, Duchateau, De Chemant, and Wedgwood. Dental ceramics will continue to exercise our minds well into the next century.

STRENGTHENING CERAMICS

Progress in dental ceramics is limited by the inherent problems of clinical dentistry: space, color, and occlusal forces. The human tooth is a very translucent object covered with a thin layer of enamel (hydroxyapatite crystals bonded in a protein matrix) of approximately 1 mm thick. The inner core of dentin nourished by the pulp is more flexible and supports the brittle enamel. Dentin consists of approximately 70% hydroxyapatite crystals bonded in a collagen matrix. Human enamel may transmit up to 70% light on a 1 mm-thick specimen, whereas dentin is more opaque and varies between 20 to 40% light transmission, depending upon the age of the tooth (McLean, 1979). In order to duplicate this translucency, dental porcelains must contain a high proportion of glassy material. Ceramics are harder than human enamel and may cause excessive wear during chewing; however, they are comparatively weak materials when compared with the gold alloys used in dentistry.

Metals possess high fracture toughness and are not so dependent on surface condition as ceramics. Indeed, many dental researchers are now realizing that the integrity of the surface of our ceramic restorations plays a major role in the longevity of the restoration, and that a high-strength ceramic with a badly flawed surface may perform worse in a clinical situation than a weaker ceramic with a comparatively flaw-free surface. For this reason the margin of safety required in ceramics is always greater than that in metals, particularly when variables in dental technology are taken into account. All dental ceramics tend to fail at the same critical strain of the order of 0.1% (Jones, 1977), and any increase in strength and toughness can only be achieved by an increase in the elastic modulus or elimination of surface flaws in the ceramic.

A number of methods for strengthening ceramics have been applied in the dental field:

1. enamelling of metals,
2. dispersion strengthening,
3. crystallization of glasses,
4. chemical toughening, and
5. bonding to thin gold or platinum foils.

Enamelling of Metals

THE METAL-CERAMIC RESTORATION

Weinstein, Katz and Weinstein (1962) first described the production of metal-ceramic restorations using porcelain powders containing 11-15% K_2O frits. Glasses in the Na_2O-K_2O-Al_2O_3-SiO_2 system containing not less than 11% K_2O when subjected to heat treatments at temperatures from 700-1200 °C produced high-expansion glasses suitable for bonding to metal at 13-15$^{10-6}$ °C. The higher thermal expansion resulted from the crystallization of leucite. The proportion of leucite is governed by the K_2O content and the temperature and time of heat treatment. The basic change required to produce a porcelain of the thermal expansion necessary for metal bonding is to increase the K_2O content to the required level, and Binns (1983) has given an average composition:

SiO_2	63.2%
Al_2O_3	17.5%
CaO	0.8%
Na_2O	5.7%
K_2O	11.7%
B_2O_3	1.0%

To achieve a strong bond to gold or palladium alloys, certain conditions must be fulfilled. The glass must wet the metal, and the stresses resulting from thermal expansion and contraction must not exceed the tensile strength of the glass.

Alloys used for attachment to porcelain must have high temperature strength and produce thin films of oxide for porcelain bonding. Dental porcelain will wet and adhere to any clean, gas-free metal, provided that the metal is covered with an adherent layer of oxide, and the temperature is raised to the point where this oxide partially dissolves into the glass. Excessive oxide production can produce weak bonding, as sometimes occurs when nickel-chromium alloys are used.

High-gold alloys containing around 80% pure gold have been used for many years, but more recently cheaper alloys have been produced that are proving successful clinically (McLean,

1988). A quiet revolution has occurred in the production of high palladium alloys that have been in use for over 12 years. An average composition is given below:

High palladium alloy	
Pd	72%
Au	2%
Cu	9.5%
Balance	Ga and Ge

The reduction in cost of these alloys and resistance to creep at high temperatures has lent an even more competitive edge to the metal-ceramic restoration, which is regarded as the strongest and most durable ceramic restoration available today. Its only disadvantage lies in the use of metal copings to reinforce the ceramic. The metal requires masking with high-covering-power opaque porcelains, and as a result the natural translucency of human teeth is lost. It is hardly surprising that research has therefore concentrated on producing high-strength ceramic restorations that allow similar light transmissions to the human tooth.

Dispersion Strengthening

Glassy materials such as dental porcelain may be strengthened by dispersing ceramic crystals of high strength and elasticity in the glass matrix. If the glass has a similar thermal expansion to the crystals, the strength and elasticity of crystal-glass composite materials may increase progressively with the proportion of the crystalline phase. McLean and Hughes (1965) used this method to reinforce porcelain jacket crowns in their development of aluminous porcelain. A core porcelain was made containing 50% (by weight) fused alumina crystals onto which a matched-expansion veneer porcelain was baked. Flexural strengths of over 120 MPa were obtained for these materials. It may be generally stated that the strength and opacity of alumina-reinforced porcelain is a function of its crystal or particle size. The finer the crystal size the greater the strength and opacity (McLean & Hughes, 1965). Research was therefore directed towards optimizing the crystal-glass particle size relationship to obtain improved sintering characteristics, strength, and acceptable translucency. Pre-fritting of fused alumina crystals in a glass melt can also improve both translucency and strength. This work resulted in the production of a number of commercial aluminous porcelains, the first being Vitadur-N (Vita Zahnfabrik, Säckingen, Germany), followed by NBK 1000 (De Trey/Dentsply, Germany), and subsequently High-Ceram (Vita Zahnfabrik). The principle of using high-strength ceramic cores has now become firmly established and led recently to further work on slip-cast alumina ceramics.

Slip-cast Alumina Ceramics

Slip-casting is the art or science of preparing stable suspensions and forming ware by building up a solid layer on the surface of a porous mold that sucks up the liquid phase by means of capillary forces (Kingery, 1958). The most common mold material used in slip-casting is plaster of Paris. The process has been used in forming clay bodies for at least 200 years, but it is only relatively recently that the principle has been applied to nonplastic materials. Count Schwerin in 1910 showed that alumina could be plasticized by grinding in acid. Fourteen years later Ruff (1924) demonstrated that several other oxides could also be treated in the same way.

THE POWDER

Slip-casting is generally carried out with most particles between the 1-5 micrometer range; few particles exceed 20 micrometers. The bulk of the particles should be in a size range where their interactions are beginning to be governed by surface forces rather than by gravity. If, however, the bulk of particles is too fine, it is difficult to exercise proper rheological control over the slip. Minor changes in the ionic atmosphere surrounding such particles can exert considerable influence on the forces of interaction and thereby cause sudden undesirable viscosity changes.

THE VEHICLE

Industrial users generally add small quantities of organics to the slip in order to improve handling of the greenware. A commonly used vehicle is a 1% solution of polyvinyl alcohol, which can strengthen the dried greenware so

that it may be carved like blackboard chalk.

IN-CERAM

Sadoun (1989) has refined the slip-casting technique to produce a high-strength alumina coping that is now marketed under the trade name In-Ceram (Vita Zahnfabrik). A pure alumina slip-cast coping is made on a special gypsum die of the tooth preparation. The greenware is dried and slowly brought to a temperature of 1100 °C for two hours. The firing process allows the alumina grains to partially fuse at their grain boundaries, and the gypsum die shrinks during the firing process. The coping may then be lifted off the die. The fit of these partially sintered alumina copings can be very accurate. Final shaping of the coping must be done at this stage, since the subsequent infusion of the glass matrix makes finishing operations very difficult because of the hardness of the final ceramic. After shaping, the porous alumina is ready for the infusion of the glass matrix. A specially prepared low-fusing glass of matching thermal expansion is painted over the external surface of the coping, which is placed on a thick piece of platinum foil. The glass melts at 800 °C, and when the temperature is raised to 1100 °C diffuses through the porous alumina by capillary action. A very dense alumina/glass composite structure results, and flexural strengths in excess of 450 MPa can be reached. Excess glass is removed by sandblasting and grinding with diamond stones, and the coping is veneered with Vitadur-N, the aluminous veneer porcelain used in the original crowns of the 1970s. The reason for continued use of aluminous-type veneer porcelain is their high resistance to devitrification during repeated firings and their matching thermal expansion to pure alumina. Aluminous porcelain enamels contain a high combined (dissolved) content of alumina, which negates the effect of sodium, causing disruption of the glass-forming lattice (McLean, 1979).

The In-Ceram coping contains at least 70% pure alumina in the body, and at the present time is probably the strongest pure ceramic available. However, it is doubtful whether this material will be successful for fixed partial dentures, since its fracture toughness still does not compare with the cast metal alloys. It is possible that small anterior bridges may be successful, but the question of surface condition related to static fatigue and subsequent fracture must be considered over the long term.

Slip-casting is not an easy technique, and requires considerable practice. Also, shaping and forming of the copings takes longer than the lost-wax technique used in metal ceramics. Undercut dies also present considerable problems, since without relief of the undercut the green coping is easily broken. However, when the copings are well made, they are accurate and translucent and form a monolithic structure with the enamel porcelains. Light scattering from the coping is reduced compared with previous aluminous core porcelains, and excellent aesthetic results can be obtained. The work of Sadoun in showing the feasibility of infusing glass into a porous alumina must be considered one of the more ingenious developments of the past two decades.

Non-shrink Ceramics

The Cerastore crown, launched 10 years ago, relied on the enamelling of a 60%-alumina body that was transfer-molded in the plastic state onto an epoxy die. This material possessed some interesting features, since it was the first non-shrink ceramic produced in dentistry. Essentially aluminum magnesium oxides were mixed with a barium glass frit that, on firing, produced a magnesium aluminate spinel. The spinel occupied a higher volume than the original mixed oxides, and compensated for firing shrinkage. A reinforcing core similar to the aluminous porcelain crown was constructed in this material onto which a matched-expansion feldspathic veneer porcelain was baked to create the tooth form. The Cerastore crown failed for two main reasons: high cost and inadequate strength when compared with metal-ceramic restorations.

Crystallization of Glasses

Controlled crystallization of glass has been tried for making artificial teeth, veneers, and crowns (MacCulloch, 1968). More recently, a crown material has been marketed under the trade name Dicor (Dentsply International, Inc, York, PA 17404), based on the work of Grossman (1983) and Adair (1984). The

material contains tetrasilicic fluormica crystals ($K_2Mg_5Si_2O_{20}F_4$), which, because of their flexibility and plate-like morphology, add strength and resistance to fracture propagation. The tetrasilicic mica system nucleates readily at a temperature of 650 °C to 1075 °C (the top hold). The residual glass phase occupies approximately 45% (volume) of the glass-ceramic.

The method of construction of the Dicor crown is very appealing, since, like all glass-ceramics, it may be cast by the lost-wax process, a traditional method used in dentistry. After "ceramming," the resulting crown is semicrystalline but still translucent like human enamel, so that it may be colored by surface staining or light glazing with several coats of porcelain veneer. Unfortunately, the strength of Dicor is no greater than aluminous porcelain, and it is doubtful whether it will withstand fracture on molars or when used to manufacture fixed partial dentures. However, when used on anterior teeth, Dicor has some distinct aesthetic advantages. Because of its high translucency, it can have a chameleon-like effect and merge with the surrounding teeth. Dicor is particularly useful for matching the adolescent tooth.

More recently, with the launching of Dicor Plus, the material is used as a cast coping and veneered with a matched expansion feldspathic porcelain of the aluminous type. This technique offers the technician the opportunity of building porcelain color in depth and utilizing the high translucency of the coping to reduce shadowing at the critical cervical margin. The design of the coping can influence the fit. When the wall thickness of the coping is reduced below 0.5 mm, there is a danger of pyroplastic flow causing distortion during the firing of the veneer porcelains. Also, on cooling, cracking of the glass-ceramic/porcelain veneer may occur. However, the principle of using a glass casting process may, in the future, reduce costs and simplify the production of highly aesthetic crowns.

Chemical Toughening

Dentistry has, over the years, investigated most avenues for strengthening ceramics, and chemical toughening is no exception.

Commercial glass products can be strengthened by as much as 10-fold or more when compared to products in the annealed state (Capps, Schaeffer & Cronin, 1980). The reported strengthening obtained for dental porcelain materials is much more modest, but still quite impressive. These ranged from 140% increases reported by Breustedt, Pahlke and Retmeyer (1975) and 47% to 122% by Southan (1970). Pendry and Bradshaw (1971) obtained a strength increase of 30% to 90%, but Jones (1977) reported only increases of up to 45% for a feldspathic porcelain.

The chemical strengthening techniques involved placing the fired crowns in platinum crucibles containing molten potassium nitrate. The potassium ion-exchange displaces sodium ions, producing compressive stresses due to crowding of the surface of the silicate network. Unfortunately, the idea never caught on due to the length of time needed to effect ion-exchange, and high strengths could only be obtained when periods of 24 to 48 hours were used.

The author has used this process, and over 50 crowns are still in service since 1972. Clearly, chemical toughening is worth pursuing if realistic periods for surface treatment of the ceramic can be achieved.

Bonding to Foils

Porcelain crowns suffer from "static fatigue," which is generally believed to be due to a stress-dependent chemical reaction between water vapor and the surface faults in the porcelain crown. This causes flaws to grow to critical dimensions, allowing spontaneous crack propagation (Jones, 1983). For this reason, when crowns have been in service for a few years, fractures may occur at comparatively low levels of occlusal loading. This may explain why patients claim their crowns fractured when only eating bread and butter.

One method of alleviating this problem was found to be the bonding of porcelain to metal foils. This procedure appears to eliminate open surface defects from which tensile failure may originate (Sced, McLean & Hotz, 1977). A method was devised by McLean and Sced (1976) whereby the surface of platinum foil was coated with up to 2.0 μm of tin; oxidation of the tin coating provided the mechanism for bonding of the porcelain. Tin-coating or thermal cleaning of the platinum matrix can in-

crease the shell strength of the core porcelain to over 300 MPa, providing that the platinum is left intact with the porcelain. When the platinum was removed, strengths fell to approximately 180 MPa (Piddock, Marquis & Wilson, 1984).

In 1979 Rogers reported a rather ingenious method of making metal copings by electroforming. He used a tin oxide coating to attach the porcelain to the gold coping, and a regular metal-bonding porcelain was used as the veneer. More recently swaged coping techniques have been used, such as the Renaissance crown or Sunrise crown. McLean and Sced (1987) reported on a 14-year longitudinal study on the use of aluminous porcelain crowns bonded to preformed platinum alloy copings. Clinical testing of 42 crowns started in 1972 indicated that a coping thickness of 0.125 mm is sufficient to prevent fracture, even in molar crowns.

What of the future? Clearly metal-bonding still has the edge over any current high-strength ceramic, since the development of crack-free interfaces is made easier and metal is not easily broken. In addition, any new technique should be submitted to a cost-benefit analysis. A preformed coping closely adapted to the axial walls of a crown preparation can be manufactured rapidly by hydraulic forming, but the question remains, how many sizes of preform are necessary? Umbrella shapes such as the Renaissance crown involve considerable problems in obtaining good fit because of thickened edges due to folding of the foil. In a further study by Sced and McLean (1987), a survey was carried out on the dimensions of 1000 dental crown preparations in order to establish a preferred range of preform coping sizes. A computer program was designed to provide values of the average maximum and minimum height and the included semi-angle for each size group. In the clinical trials it was found that three preform sizes covered a large number of the premolar cases; all premolar cases were covered by five sizes. In the case of anteriors, up to 40 sizes were required, but in practice this could be reduced, particularly if the coping was only used to restore the axial walls.

Future research would probably best be concentrated on developing a preform pure platinum coping of 0.1 mm thickness, which is gold-plated to improve color, as Rogers (1979) has suggested. This coping could be swaged and fitted to the axial walls of the preparation and then transferred to a refractory die prior to baking the shoulder porcelain. By this means a collarless bonded alumina crown could be made that avoids metal shadowing at the cervical and also provides long-term resistance to fracture.

EVALUATION OF NEW CERAMIC SYSTEMS

The overriding requirements for any porcelain crown should be aesthetics and strength. Unfortunately the two properties conflict. To obtain maximum strength, the ceramic must contain a high proportion of crystalline material such as alumina, which increases opacity due to mismatch in refractive index between crystal and glass phase. For this reason all the current crowns except Dicor use a coping similar in design to a metal coping over which a translucent veneer can be built. The new material In-Ceram can provide the most translucent coping of all the alumina systems, but requires more skill in fabrication. As yet no all-ceramic system is suitable for posterior or large anterior fixed partial dentures. At present all these systems are better confined to anterior teeth where aesthetics is of major concern. The metal-ceramic restoration remains the crown of choice where accurate fit, strength, and reasonable aesthetics can be achieved without involving costly or elaborate procedures. For the individual anterior crown the swaged coping technique has great development potential.

PORCELAIN VENEERS

In the last few years a technique of making thin porcelain laminates for attachment to anterior teeth has grown in popularity (Simonsen & Calamia, 1983; Horn, 1983; Calamia, 1983). Approximately 0.5 mm of facial enamel is removed and both porcelain and enamel are acid-etched prior to using a light-cured or combined light and chemically cured resin cement to unite the two structures.

Porcelain veneers have performed better than many scientists predicted. However, on a long-term basis, the effects of "static fatigue" still need to be assessed. Continuous loading in a wet environment can deepen microcracks to the point where catastrophic failure may occur. Although failures occur, many clinicians are

reporting great success with veneers; this may be due to the intimate bonding of the resin cement distributing stress more evenly. Shear forces may be less than were thought in the labial area. Theoretically, the resin cement and porcelain veneer act as a constant strain system, where any loading is transferred to the higher modulus material (the porcelain veneer). If the critical strain region of 0.1% is reached, then fracture will occur. Bonding to dentin is less favorable than to enamel, not only because of the doubtful efficacy of dentin bonding agents but also because extensive areas of lost enamel reduce the stiffness of the tooth, which may contribute to breakage of the veneer. In general, the intra-enamel preparation produces the least stress in the laminate veneer.

Perhaps the major functional problem with the porcelain veneer lies in its accuracy of fit. Very few veneers can be made with a marginal accuracy of less than 20 μm, and most of them are nearer 100 μm. These open margins have to be sealed with resin cement, and the wider the margin, the greater the risk of hydrolytic instability of the resin playing a part in either debonding or marginal staining. A further disadvantage of the porcelain veneer is that in thin sections the porcelain tends to become monochromatic and lacks the breakup of color present in natural teeth. The problems for the dental technician are two-fold. If the veneer is too translucent, there is a tendency for high spots to appear in areas of varying dentin or porcelain color despite the use of colored cements. This applies particularly where there are sharp demarcations of color in the tooth. On the other hand, when a more opaque base is used in constructing the veneer, then it is difficult to avoid monochromaticity produced by lack of translucency in the incisal enamel and contrasting dentin color.

The porcelain veneer is particularly useful as an interim procedure for cosmetic or minor functional correction of children's teeth, e g, rotated or lingually inclined incisors, spaced teeth, or defects in calcification. Crown preparations on adolescent teeth are notoriously difficult and the biological consequences are well known, particularly the effects of infringing the biological width with too deep a shoulder preparation. Porcelain veneers are rarely suitable for restoring worn or severely destroyed dentitions in the adult, and lingual metal backings are often essential in order to preserve occlusal stability. In the adult tooth, a porcelain veneer is likely to be more successful where the tooth is comparatively intact and can give full support to the porcelain shell. Prior to embarking on porcelain veneers, the clinician must be assured of first-class technical support and realize that meticulous treatment planning and tooth preparation are essential. The porcelain veneer is not the simple solution to aesthetics that many people believe. Color, fit, and longevity pose major problems.

THE FUTURE

Within the foreseeable future it is unlikely that the metal-ceramic crown or fixed partial denture will be replaced by pure ceramics, particularly with the introduction of the much cheaper high-palladium alloys. Teeth are such complex structures that it is difficult to envisage the replacement of hand-crafting with automated procedures. Dental ceramics remains an art as well as a science. Computer-aided machining of glass-ceramics or porcelain may become routine, but anterior crowns cannot be made in one color without sacrificing aesthetics.

The principle of using high-strength ceramic cores veneered by hand with feldspathic glass veneers is capable of further development. In addition, bonding to thicker swaged foils of platinum or gold alloys may be another route to develop high strengths. Without some form of metal bonding to alleviate "static fatigue" in service, it is difficult to see how we can construct molar crowns or bridges that will resist high stress, particularly in the central fossae of molars. The microcrack in ceramics remains the Achilles heel of dental crown and bridgework.

However, in the last 20 years, research in dental ceramics has accelerated and outpaced anything that has been done in the earlier part of this century, and the public have come to accept that diseased or abraded teeth can now be replaced with artificial materials that defy detection even by the professional eye. Research in dental materials during the last 30 years has made significant advances, ranging from metal-ceramics, composite filling materials, polycarboxylate and glass-ionomer cements, aluminous porcelains, machinable glass-ceramics, urethane dimethacrylate resins,

visible-light-cured resins, composite/glass-ionomer restorations and cermet-ionomer cements. These materials have transformed the treatment given to the public; modern dentistry can now offer microsurgical techniques and adhesive bonding in place of the old concept of simply filling a tooth. It is hoped that within 20 years a new generation will grow up taking advantage of this new research, and we can enter an era where the dental chair is no longer regarded with the same apprehension that it is so often today.

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POINT OF VIEW

Contributions always welcome

In Defense of Amalgam

JOHN W OSBORNE

Dentists have a number of choices when rebuilding a tooth. Besides amalgam there are ceramics, composites, cast materials such as gold, and base metal alloys. If you looked at these latter materials, you'd be struck by the fact that they are in many cases aesthetic and/or very appealing. Amalgam, on the other hand, is not pretty. Why then do we use it? We've been placing it for 150 years; we placed over 100 million last year, and 92% of dentists list it as our material of choice in the posterior of the mouth (Clinical Research Associates, 1990). Are we wed to it? No! The reasons we use it so frequently are quite simple. First, its durability. Numerous studies have been conducted on the serviceability of amalgam. Most of these have been on the old low-copper alloys, and indicate that they last 8-15 years (Baillit & others, 1979; Robbins & Summitt, 1988; Qvist, Thylstrup & Mjör, 1986; Allan, 1977). We have made vast improvements in the past 20 years with the development of the high-copper amalgams. Clinical studies initiated in the mid-1970s at Indiana (Osborne & Norman, 1990; Osborne, Norman & Gale, in press), Kentucky (Laswell & others, 1989), and in The Netherlands (Letzel & others, 1989) are reporting that a well-placed high-copper amalgam will last over 30 years. No other material gives us this durability. The second reason is the ease with which amalgam is placed and manipulated. Placement of an amalgam will take only 20% to 50% of the time it takes to place other restoratives in the posterior of the mouth. Therefore the cost to rebuild a tooth is considerably less. This does not mean that the other materials are not used when there are indications for them, but amalgam is the material of first choice.

Dentists recognize that mercury vapor is released from amalgams. The question is not if, but how much. There have been several reports quantifying the amount of mercury vapor released from amalgam. Vimy and Lorscheider (1985) suggested that 8 to 29 μg of mercury were released every 24 hours. This range was for 4 to 12 occlusal amalgams. Mackert (1987) recalculated these figures and found they were high by a factor of 16. Berglund (1990) reaffirmed that the Vimy and Lorscheider report was high by showing that 1.7 μg of mercury vapor was released in a 24-hour period from amalgams. This is insignificant when compared to allowable mercury exposure. Berglund pointed out that the 1.7 μg per day for amalgams is about 1% of the allowable mercury exposure for workers. Now, I don't pretend to be a toxicologist, but as a clinical researcher and practitioner, it seems clear to me that toxicity is a relative concept, and we must keep the doses here in perspective.

I am often asked, "What do you tell your patients when they ask about amalgam?" Briefly, because of the lack of time, I tell them that mercury has been a factor in human life since

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we first walked on this earth. It is in the air, in water, and in our food: not just fish, but tomatoes, cucumbers, and bread--all of it. Doing some research recently at San Antonio, I found mercury in my underarm deodorant and my lemon-lime shave cream, and I know it's in my wife's opthalmic solution. I explain toxicity by saying that most items can be toxic; it's the dose that's critical. I use salt as an example, for it can be lethal if too much is taken at one time. I discuss techniques used in the office to minimize mercury exposure, such as use of rubber dam and precapsulated amalgam alloy. Lastly, and most importantly, I explain to patients that there is a group of people who have higher levels of mercury than they have--dentists. Dentists work around mercury on a routine basis, and we can even see the level rise from the time when they enter dental school through their four years of education. Since dentists are exposed to more mercury than the general population, any problem should show up in us. And when you examine the reports on health and mortality and morbidity rates, you find something very interesting. Dentists are healthier than the general population; in fact, they are healthier than their physician colleagues. They die of the same causes, but they live a little longer. Dentists are not dying of unusual diseases. We don't get cancer at a higher rate, don't have more multiple sclerosis, arthritis, heart attacks, or any other diseases. If this was one or two reports, we could question it, but I've reviewed 18 from a number of sources (Putman & Madden, 1972; Zwemer & Williams, 1987; Galginaitis & Gift, 1980; Howkins, 1935; Bernstein & Balk, 1953; Austin & Kruger, 1947; Bureau of Economic Research and Statistics, 1963 & 1975; Orner & Mamna, 1976; Simpson & others, 1983; Milham, 1972; Glass, 1966; Blachley, Osterud & Josslin, 1963; Brodsky & others, 1985; Black, Rathe & Goldstein, 1990; Enwonwu, 1987; Orner, 1978; Eccles & Powell, 1967).

This is my bottom line to my patients and to you: if there is a problem with mercury, then it should be found in dentists, for we routinely have levels higher than the general population. As a dentist I just don't see the evidence to support any change in the way we regulate or use amalgams.

What I do see is that there will be a pronounced effect on the public health if there is a classification change in amalgam. We know that other materials don't hold up as well as amalgam. As an example, if a 10-year-old child gets a restoration of amalgam, it may have to be replaced only once in his or her lifetime. If that 10-year-old gets a material that lasts 12 years, and I'm being generous in the case of some of the other materials, she or he will have it replaced five times. The problem is that the tooth won't withstand five replacements. Each time the tooth is worked on the preparation gets larger; this weakens the tooth and increases the chance for a root canal. Unfortunately, these teeth that are worked on several times are lost and then bridges and/or partial dentures are required. Without amalgams, many patients will go through this cycle, and it will have a negative effect. Millions of dollars are being spent on developing new materials and improving existing ones, and yet amalgams have withstood the test of time. If the public perception is changed about amalgam, there will not be a question of dentists being busy--we will be very busy! I'm afraid this will have its biggest impact on lower-income patients, large health delivery programs such as the VA, dental insurance programs and, in particular, any underfunded public health agency.

In summary, dentistry placed over 100 million amalgams last year. As with all medical/dental procedures, there is a degree of risk. We must carefully evaluate these risks. All things considered, amalgam represents the best material available to the profession, and presently there is no substitute. Any problem associated with mercury should show up in dental care providers, for we have greater exposure than our patients. And this we do not see in the health statistics.

I do not have a vested commercial interest in amalgam. I'm not selling books or any device related to amalgams. My interest is in providing the best care to my patients.

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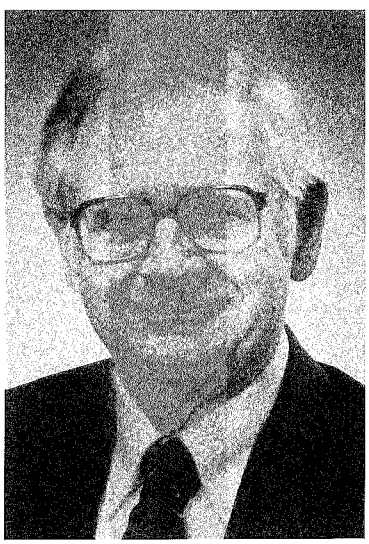
In Memoriam

The international dental community lost a renowned scientist, teacher, and lecturer with the death of Dr Ralph W Phillips on 17 May 1991. Dr Phillips, who was for decades one of the world's foremost authorities in the field of dental materials science, held the distinguished rank of Research Professor Emeritus of Dental Materials at Indiana University School of Dentistry. He died in Indianapolis at the age of 73.

Throughout an eminent career that spanned 50 years, Dr Phillips was widely recognized as one of the most dynamic and sought-after lecturers in dentistry; he appeared on more than 1000 programs around the world. He organized and chaired more than 40 symposiums and conferences related to biomaterials and dental research.



Ralph W Phillips

When he was first recruited by Indiana University to help develop a dental materials program in the 1940s, Dr Phillips designed and built most of the equipment himself. In addition to chairing the department of dental materials for several decades, he was appointed Indiana University's first associate dean for dental research and served for a time as director of IU's Oral Health Research Institute.

As a pioneer in research, Dr Phillips was one of the first to investigate the relationship between laboratory tests and clinical performance. He initiated clinical investigations designed to evaluate the effect of the oral environment upon restorative materials and to determine the efficacy of new formulations and techniques of usage. As others began to recognize the importance of this approach, clinical investigation of materials became an essential component of all meaningful research programs in the discipline. Dr Phillips' award-winning studies of the influence of fluoride solutions on the acid solubility and hardness of enamel were instrumental in the acceptance of fluoride therapy. He also recognized and demonstrated through a number of experiments that fluoride could be added to restorative materials to increase their anticariogenicity.

In the 1960s, Dr Phillips coordinated the first workshop in adhesive dental materials, bringing together scientists with special knowledge in the areas of adhesion, polymers, and tooth structure. Recommendations from that workshop and the published proceedings triggered an avalanche of interest and research in the field. In the following years he co-chaired two more workshops, and for the first time a collaborative research program was established between the National Institutes of Health and profit-making institutions to implement investigations of adhesive dental materials. The monitoring committee for reviewing research in this area was chaired by Dr Phillips for the six years of its existence.

A prolific author, Dr Phillips wrote more than 300 scientific papers and books, including his major work, *The Science of Dental Materials*, which has been one of the most widely used and translated dental textbooks in history. Dr Phillips had recently completed the ninth edition, which was published in March 1991. He also served on the editorial board of a number of professional journals and was an editorial advisor for *Operative Dentistry*. The recipient of many awards and honors, he held a Gold Medal Award from the Pierre Fauchard Academy, a William J Gies Award from the American College of Dentists, the Hollenback Memorial Prize from the Academy of Operative Dentistry, and a Wilmer Souder Award from the International Association for Dental Research.

Ralph was a dedicated professional. He was loved and respected by all he encountered. He made a profound impact on our profession and will be missed very much by each and every one of us.

Mrs Phillips requests that any donations given in his memory be made to the Indiana University Foundation, Dental Materials Department, or the Omicron Kappa Upsilon Scholarship fund. Donations may be sent to the attention of Jan Hodgin at the Indiana University Dental School, 1121 W Michigan St, Rm 118, Indianapolis, IN 46202.

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