In vitro enamel effects of a resin-modified glass ionomer: fluoride uptake and resistance to demineralization

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Abstract

Purpose: The purpose of this study was to determine the in vitro effects of a resin-modified glass-ionomer restorative material on human enamel.

Methods: Enamel specimens were restored with Photac-Fil, a resin-modified glass ionomer; Ketac-Fil, an autopolymerizing glass ionomer and silver amalgam. The samples were pH cycled and then subjected to an artificial caries challenge. Specimens were evaluated by fluoride microdrill biopsy and quantitative microradiography at 1, 2, and 3 mm from restorations. Data on fluoride content, lesion depth, and mineral content were analyzed by one-way ANOVA, Student's t test, Neuman-Keuls procedure (multiple [pairwise] comparison), and Pearson's product-moment correlation tests.

Results: There were significant differences in fluoride uptake, lesion depth, and mineral density between groups. Significant correlational relationships were also determined.

Conclusion: This study demonstrates that Photac-Fil and Ketac-Fil prevent in-vitro demineralization of enamel and suggests different mechanisms of action for each material. (Pediatr Dent 20:411–417, 1998)

Resin-modified glass-ionomer materials (RMGIMs) are finding increasing use by dental practitioners in the United States and offer a dual preventive and restorative material for caries rehabilitation in pediatric patients.[1, 2] Indications for these materials include Class I, III, and V restorations in primary teeth, fissure sealants, temporary restorations, and orthodontic bonding.[1, 3] Resin-modified materials differ from autopolymerizing glass ionomers (GIs) by the presence of polyacrylic acids and photoinitiators.[4] In comparison to GIs, the resin-modified materials demonstrate improved fracture toughness, wear resistance, optical properties, and handling characteristics.

Concurrently, chemical adhesion and fluoride release and uptake, desirable physical properties characteristic of GIs, are partially or totally maintained in RMGIMs.[3, 5, 6]

In vitro studies demonstrate that fluoride-release patterns and amounts vary according to class of material, proprietary formulation, and storage media. For example, GIs release significantly more fluoride than RMGIMs in distilled water but comparable amounts in synthetic saliva.[7, 8] Product formulation and material classification may also influence release kinetics. Differences in the fluoride-release kinetics of these materials may ultimately translate to differences in the response of marginal enamel to acid attack.[9] Qualitative polarized-light microscopic work has demonstrated resistance to demineralization at GI and RMGIM restoration margins.[10] Although this information is pertinent to the development of recurrent caries, there has been little quantitative data presented on fluoride uptake into enamel both at, as well as distant from, the margins of restorations.[11–13] Such information may extend our understanding of the role that fluoride from restorative materials plays in cariostasis.[14]

Mechanistic actions of fluoride in caries prevention are dependent on concentration of fluoride and hydrogen ions. In low concentrations and in the presence of acid and calcium phosphates, fluoride in the oral cavity is a component of a competitive and dynamic iso-ionic exchange reaction that alters hydroxyapatite into a fluoridated form by crystal growth.[15] At higher concentrations, a calcium fluoride-like material is formed on the enamel surfaces and over time, is released to form fluorapatite as mentioned above.[16, 17] This has been shown to occur with fluoride-releasing orthodontic bonding materials.[12] The resultant fluorapatite-rich enamel is more resistant to acid attack and has increased microhardness.[18]

Although numerous glass ionomer studies verify that fluoride release occurs in varied concentrations dependent on material and time, the mechanistic interaction of these materials and calcified dental tissue is unclear.

The aims of this study were to:

1. Determine in vitro enamel fluoride uptake from a RMGIM

2. Characterize and quantify the effects of a RMGIM on in vitro enamel demineralization by microdensitometry

3. Compare enamel fluoride uptake and quantitative microdensitometric effects of a RMGIM with a GI.

Methods

Human unerupted extracted third molars were sectioned to produce 30 enamel slabs from buccal and lingual surfaces measuring approximately 3 x 4 x 6 mm. These specimens were embedded in sticky wax on acrylic discs and plano-paralleled on silicon carbide lapping paper, thereby removing the outer fluoride-rich layer. Using a #56 tungsten carbide bur (Brasseler, Savannah, GA), troughs were created across the total width and at one end of each enamel slab to a depth of 1.0 mm. This polar positioning of preparations was selected to optimize a contiguous enamel surface for evaluative techniques. Enamel samples were randomly assigned to restorative material groups: Photac-Fil Aplicap (PF) a RMGIM, Ketac-Fil Aplicap (KF) a GI (Espe, Norristown, PA), and Tytin® amalgam (A) (Kerr, Romulus, MI) which were placed in specimen preparations following manufacturers' instructions. Caution was exercised during material placement to minimize enamel surface contamination beyond the margins of the cavity preparation. PF was polymerized for 40 s using a curing light (Espe GmbH + Co.KG, Seefeld, Germany). All enamel/wax margins were then sealed with acid-resistant varnish.

The grouped specimens were placed in an incubator at 37°C and 100% humidity for 24 h. The specimens were then subjected to pH cycling for 16 h in remineralizing solution pH 7.2, and 8 h in 0.1 mol/L lactic acid at pH 5.0. The alternating sequence of remineralization followed by demineralization was continued for 14 days. Throughout this period, the specimens were maintained at 37°C.[19–21] The total length of time was determined by fluoride-release studies that indicate maximal release occurs during this period.[7, 8] All samples were rinsed with distilled water between remineralizing and demineralizing components of the cycle and stored collectively by group in three glass jars. The samples were then placed in 0.1 mol/L lactic acid at pH 5.0 for 196 h continuously and stored as described above. This represented an artificial caries challenge.

Specimens were thereafter removed from and rinsed of the acid with distilled water and let to dry at room temperature for 24 h. Each enamel slab was then embedded in sticky wax on an epon cylinder and placed
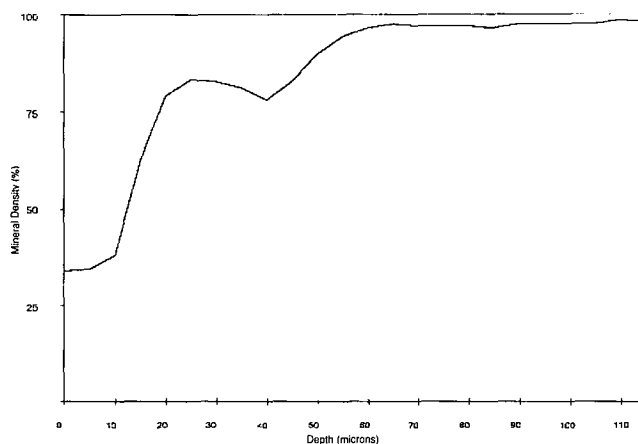

Fig 1a: Microdensitometry of artificial enamel caries in Amalgam group.
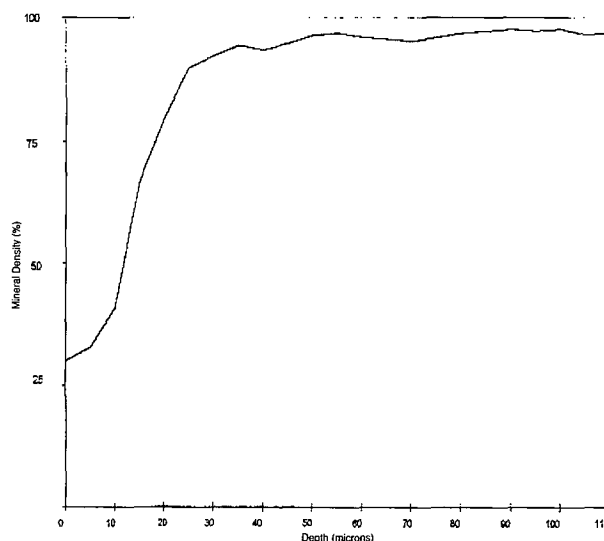

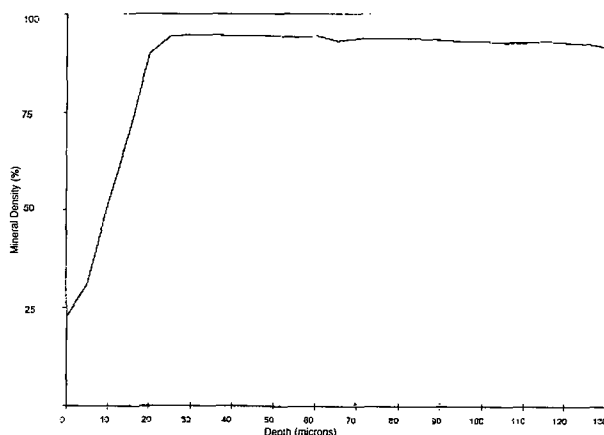Fig 1b: Microdensitometry of artificial enamel caries in Ketac-Fil group.

Fig 1c: Microdensitometry of artificial enamel caries in Photac-Fil group.

on a lucite pedestal in preparation for microdrill biopsies.[22] Linear fluoride biopsies were taken at 1, 2, and 3 mm from each restoration using a round diamond bur (Brasseler, Savannah, GA) to a depth of 100 μm. The resultant dust was collected in a scintillation vial. All 90 microdrill biopsies were individually dissolved in 0.25 mL of 0.5 mol/L perchloric acid, 0.5 mL of TISAB (Orion Research, Cambridge, MA) and 0.25 mL of 0.5 mol/L sodium hydroxide at pH 5.5. Addition of 0.5 mL of 2 ppm sodium fluoride standard was made to each vial and direct fluoride measurements were made using a fluoride-ion sensitive electrode (Orion Research, Cambridge, MA) and recorded in ppm. This was converted to $\mu g/mm^3$ of enamel. The addition technique was used due to the microconcentrations of fluoride which may not have been registered accurately by the electrode.

After the microdrill biopsies, each enamel specimen was embedded in epoxy resin (Epon 812) and incubated for 36 h at 55°C. Serial microsections perpendicular to the exposed enamel and measuring approximately 150 μm were made of each sample with a high-speed microtome (Scientific Fabrication, Littleton, CO). These were not polished due to the friable nature of the enamel. Microradiographs of each section were produced on Kodak™ SO 343 film for 22 min at 15 mA and 20 kVp with an X-ray generator and tungsten anode (Faxitron 43855A, Hewlett

Packard). An aluminum step-wedge standard and an endodontic radio-opaque grid (Medidenta International, New York) were included in each microradiograph. The grid separations were 1 mm apart. Image analysis of the topmost or surface 100 μm of enamel was performed using microscopy and digitized computing (Cybernetics, Silver Spring, MD). This depth was determined to correspond with the microdrill biopsy depths. The step-wedge standard and radio-opaque grid were used for intensity and spatial calibration. Microdensitometric spatial measurements of line-profiles perpendicular to the exposed enamel surface were analyzed and recorded as depth (μm). Per-area intensity counts were made in corresponding enamel regions and reported as percent mineral density. "Per-area" denotes the computer scanning technique for measuring gray levels within the defined area. Intact enamel at the base of the defined 100-μm depth was considered 100% dense, and gray areas within the lesion were recorded relative to that. Intact enamel therefore would show static range and demineralized enamel a dynamic range graphically, based on uniformity or disparity of gray levels respectively. The data was plotted on x and y axes (Figs 1a–c).

All fluoride biopsy samples were randomly labeled and concentration measurements were made by one blinded examiner. For the microradiographic evaluations, the same examiner was not uniformly blinded as amalgam samples were characteristic in their appearance. In addition, some but not all restorations fell out during microsectioning.

Fluoride content, depth of lesion, and percent mineral density between material groups and within groups between distance were analyzed using one-way ANOVA. Neuman-Keuls (multiple [pairwise] comparison) procedure isolated groups displaying differences.

Pearson's product-moment correlation coefficient was used to identify any relationship between fluoride content, depth of lesion, and percent mineral density.

TABLE 1. ENAMEL FLUORIDE UPTAKE ($\mu G/MM^3$)

Between Groups	PF (Mean ± SD)	KF (Mean ± SD)	A (Mean ± SD)
	0.97 (0.42)*	0.87 (0.42)*	0.56 (0.18)
Within group			
1 mm	0.83 ± 0.33	0.80 ± 0.56	0.63 ± 0.19
2 mm	0.92 ± 0.31	0.90 ± 0.32	0.55 ± 0.19
3 mm	1.16 ± 0.54	0.91 ± 0.38	0.51 ± 0.17

* Statistically significant $P < 0.05$.

TABLE 2. ARTIFICAL CARIES LESION DEPTH (μM)

Between Groups	PF (Mean ± SD)	KF (Mean ± SD)	A (Mean ± SD)
	23.3 (13.73)*	17.9 (11.70)*	54.5 (9.24)
Within group			
1 mm	20.0 ± 14.88	13.8 ±12.46	53.9 ± 4.38
2 mm	25.6 ± 13.21	19.4 ± 13.21	57.9 ± 11.85
3 mm	24.4 ± 14.25	20.6 ± 9.43	51.7 ± 10.11

* Statistically significant $P < 0.05$.

Results

After pH cycling, all A specimens displayed a chalky white appearance on all exposed enamel. This was more apparent after the artificial caries challenge. Varying degrees of decalcification were also observed in KF and PF samples 3 mm from the restoration. Enamel regions abutting and up to 2 mm from KF and PF restorations displayed a glassy translucent appearance.

Statistically significant differences were found for fluoride uptake among treatment

TABLE 3. ARTIFICIAL CARIES LESION MINERAL DENSITY (%)

Between Groups	PF [Mean (SD)] 78.0 (8.70)*	KF [Mean (SD)] 77.4 (8.90)*	A [Mean (SD)] 59.2 (9.71)*
Within group			
1 mm	78.1 (8.92)	80.1 (7.88)	57.3 (9.41)
2 mm	79.0 (8.65)	77.4 (9.69)	59.3 (9.55)
3 mm	76.9 (9.58)	74.6 (9.33)	61.1 (11.22)

* Statistically significant $P < 0.05$.

TABLE 4. ENAMEL FLUORIDE UPTAKE, LESION DEPTH, AND MINERAL DENSITY (R)

Correlation	Fluoride Uptake	Lesion Depth	Mineral Density
		PF	
Lesion Depth	(–) 0.13		
Mineral Density		(–) 0.79*	
Fluoride Uptake			(+) 0.18
		KF	
Lesion Depth	(+) 0.66*		
Mineral Density		(–) 0.83*	
Fluoride Uptake			(–) 0.59*
		A	
Lesion Depth	(–) 0.01		
Mineral Density		(–) 0.61*	
Fluoride Uptake			(–) 0.07

* Statistically significant $P < 0.01$.

groups, specifically between PF and A and KF and A ($P < 0.05$). Enamel abutting PF contained more but nonsignificant fluoride than KF (Table 1).

There were no significant differences within any group at distances 1, 2, and 3 mm ($P < 0.05$). Nevertheless, there was a trend in both ionomer groups for increased fluoride uptake and distance from the restoration. However, this was not the case with A, which showed decreased fluoride content further from the restoration (Table 1).

Lesion depth differences were found among treatment groups (Table 2). As with fluoride uptake, this was significant between PF and A and KF and A and nonsignificant between PF and KF ($P < 0.05$). In addition, KF showed the least depth and amalgam the most.

No significant differences within groups at distances 1, 2, and 3 mm were recorded ($P < 0.05$). A pattern of increasing depth with distance from restoration was evident with KF but with no other group. There was a wide range of lesion depth with PF and KF (Table 2).

Both PF and KF groups were significantly more radiodense than A ($P < 0.05$). Ionomer materials were not significantly different (Table 3).

Although there were no significant differences within groups between distances, there was distinct mineral density variation with each material. KF had decreasing mineral density with increasing distance. By contrast there was increasing mineral density and distance in group A, and no apparent pattern in PF (Table 3).

Significant positive correlations were found between fluoride uptake and lesion depth for KF ($P < 0.01$). Negative correlations between mineral density and fluoride uptake were present for KF and between lesion depth and mineral density for all groups (Table 4).

Discussion

The pH-cycling system used in this study has been reported in few investigations of fluoride release from dental materials.[11] Most studies have employed distilled water, synthetic saliva, or lactic acid. In the present study, both synthetic saliva and lactic acid were used in the pH-cycling phase and then lactic acid used for the artificial caries challenge. De- and remineralizing effects of fluoride are dependent on the presence of hydrogen, calcium, and phosphate.[15, 16] The cycling system provided a dynamic ionic environment for this to occur and is more representative of the oral cavity than a monophasic solution such as distilled water.

An extensive pilot experiment was undertaken to create artificial caries in the enamel of both amalgam and glass ionomer groups that would withstand microsectioning. With varied acidic pHs used in the pilot study, amalgam enamel was consistently either partially or totally denuded while the enamel abutting glass ionomer was virtually intact. This would have precluded subsequent specimen preparation for microradiographic evaluation, and may have been a function of the pH cycling combined with released fluoride resulting in highly mineralized enamel in the ionomer groups and cavitated enamel in the amalgam group. Consequently, the artificial caries challenge parameters used in the present study were of higher pH and of longer duration than work quoted in the literature.[21, 23]

A fluoride-evaluation technique commonly used in glass-ionomer investigations is the acid etch method. It involves sequential etching procedures and necessitates calcium and phosphate assays to estimate depth. If used in this study, the technique would have presented problems related to possible inclusion of material in the biopsy, demanded additional experimental procedures for calcium and phosphate assay, and necessitated preparation of separate specimens for microradiography. The microdrill biopsy technique used in this experiment allowed for definitive and controlled depth and location without contamination from fluoride-containing restorative materials. It also afforded latitude for microradiographic analysis of the same enamel specimens at corresponding fluoride biopsy regions. The microdrill biopsy technique presented advantages over the acid etch method for the purposes of this study.

In preceding investigations using the microdrill technique, tungsten carbide burs have been used successfully in dentin and demineralized enamel.[22] However, in the pilot experiment, a tungsten bur was unsuccessful in obtaining biopsies from PF enamel and only penetrated enamel to limited depths with KF. Enamel exposed to PF and KF were minimally demineralized and may have been similar to, or harder than intact enamel. A diamond bur was effective in collecting enamel from all groups and therefore was used in this experiment.

Aluminum released into distilled water from glass ionomer materials in the first 7 days of release has been demonstrated to interfere with electrode readings.[24] This study did not evaluate the fluoride released into solution for a corresponding period, but rather fluoride uptake by enamel over 2 weeks under pH-cycling conditions. Although aluminum has an in vitro inhibitory effect on demineralization, it was not addressed in this study.[25] The effects of aluminum on fluoride measurements and enamel demineralization under the conditions of this study are unclear and may be determined through further study.

De- and remineralization qualitative studies evaluating changes in enamel have utilized polarized-light microscopy for zone identification. The technique further enables quantitative measurement of the extent or size of the lesions. Microradiography provides additional quantitative data on changes in mineral density and therefore offers a more comprehensive quantitative assessment than polarized-light microscopy, and was thus used in this study. Microhardness testing quantitatively assesses mineral softening and would be appropriate for studies addressing such changes.[26]

From macroscopic and microradiographic observation, there was no evidence of flash from any material group. This was a concern in material placement as excess material may have led to registration of aberrant fluoride biopsies from a combination of material and enamel. Microradiographical findings may also have been influenced by overhanging material. Based on the results of this work, it appears that the restorative materials were effectively placed within the troughs consistent with goals of methods design.

In conformity with studies testing fluoride release into synthetic saliva, PF enamel contained higher albeit nonsignificant fluoride levels than KF.[7] This may be related to the amount of fluoride released by the restorative in the presence of cations found in synthetic saliva. This is contrary to release patterns in distilled water, where release is higher in autopolymerizing glass ionomers.[8]

Fluoride uptake increased with distance for both glass ionomer restorations. This may have been due to elevated fluoride levels closer to the restoration, resulting in lower dissolution of enamel.[27] Subsequently, there would be lower enamel fluoride uptake. This corroborates current theories of fluoride's cariostatic mechanisms.[15-17, 27] Enamel that was 3 mm from the restoration showed features of demineralization and differed from areas closer to the restorations. There was higher fluoride at 3 mm in support of the theories of fluoride uptake by crystal growth or calcium fluoride formation in the presence of acid. In contrast, amalgam had decreasing amounts of fluoride further from the restoration which may have been due to reduced mineralization distal from the restoration corresponding with cervical enamel.

This study shows that under in vitro conditions it was difficult to create artificial caries lesions in permanent human enamel in proximity to PF and KF. Glass-ionomer fluoride-release literature has not as yet demonstrated a clear dose/response relationship, or critical level for effective resistance to demineralization of tooth material. Fluoride levels in pH cycling fluids or artificial caries acid were not evaluated. Investigations focusing on ambient levels of fluoride and other ions in fluids in contact with glass ionomer materials may further elucidate dose/response factors.

The appearance of amalgam specimen lesions was characteristic of reports of in vivo and in vitro incipient caries literature.[28] However, the mean depth was lower than is quoted by investigators due to the conditions in this work.[29] Lesions in both glass-ionomer specimens were shallow and less uniform in depth when compared to amalgam. Fluoride release has been shown to vary widely even within an individual proprietary material and may have had a diverse effect on de- and remineralization of dental hard tissue in this study.

Within groups, there were varied mineral density/distance patterns. KF decreased and A increased with distance. PF did not follow either of these trends. Microradiographic investigations have indicated mineral density between 66 and 50% in nontreated enamel and mean mineral density fell within this range for the

amalgam group.[28-30] As with depth, the relatively higher mineral density at 3 mm in this group may have been due to its proximity to the acid resistant varnish seal close to the enamel/wax margin. Enamel juxtaposed to KF was high in mineral content, which decreased further from the restoration.

Correlations found between fluoride uptake and lesion depth differed significantly between PF and KF. This unexpected finding may have novel implications related to mechanistic aspects of prevention from fluoride releasing materials. KF lesion depth increased consistently with fluoride content whereas this was not seen with PF. This indicates that fluoride was incorporated in the shallow decalcified areas in KF, in the underlying highly mineralized regions up to 100 μm, or both. According to theories of fluoride mechanisms of action, this may have been in a surface calcium fluoride-like form or loosely bound in enamel pores, thereby preventing further demineralization.[16] KF releases relatively high amounts of fluoride in distilled water and synthetic saliva, and probably released adequately high concentrations to support remineralization and uptake by enamel. The findings of this study corroborate fluoride uptake with decalcification as proposed in the literature.[15, 16]

KF had a significant negative correlation between fluoride uptake and mineral density. This data presents increasing fluoride content with decreasing mineral density, suggesting that enamel fluoride was not remineralized and was probably in loosely bound or calcium fluoride-like phase. Calcium and phosphate analyses and qualitative crystallographic or spectroscopic evaluation of components of the lesion would characterize mineral phases and further illustrate mechanistic effects of fluoride-releasing restorative materials.

PF data did not feature a similar significant correlation between fluoride uptake and lesion depth. A possible reason for the low correlation is the propensity for RMGIMs to release and take up fluoride. This may have resulted in a lower, slower, and consistent release rate supporting low fluoride concentration with concomitant iso-ionic exchange mechanisms.

In contrast to KF, PF had a weak, nonsignificant positive relationship between mineral density and fluoride uptake. This may suggest the possibility of remineralization as evidenced in several specimens that were hypermineralized at the outermost enamel. Future work with more robust sample sizes may verify this relationship.

Expectedly, significant negative correlations were consistent for all groups between mineral density and lesion depth.

Though in vivo situations cannot be extrapolated directly from in vitro work, the results of this study present new perspectives on mechanistic aspects of fluo-

ride-releasing glass-ionomer materials on mineralized tissue. There is little literature in this area and further in vitro and clinical research may result in the development of an optimally effective intraoral fluoride-releasing device in the form of a restorative material.

Conclusions

Based on the results and conditions of this study:

1. Comparable in vitro fluoride uptake occurs in enamel surrounding Photac-Fil and Ketac-Fil restorations.

2. Photac-Fil and Ketac-Fil restorations impart comparable resistance to demineralization to surrounding enamel in vitro.

3. Fluoride released by Photac-Fil and Ketac-Fil may provide in vitro enamel resistance to demineralization by different mechanisms of action.

4. Further investigation is required to determine mechanistic aspects of fluoride released from restorative materials.

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Acknowledgments

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